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17

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Indexes in #4 (53) x #4 (54)

## « CONTENTS »

Illite and Montmorillonite in Green Sedimentary Rocks ..... *W. D. Keller* 3

Analcime in the Chinle Formation of Utah Correlative with the Popo Agie of Wyoming ..... *W. D. Keller* 10

Evidence of Biochemical Heating in Lake Mead Mud ..... *Claude E. Zobell, Frederick D. Sisler and Carl H. Oppenheimer* 13

The Origin of the Deposits of Tufa in Mono Lake. . *James R. Dunn* 18

Rafted Pebbles from the Deep Ocean Off Baja California ..... *George A. Shumway* 24

Correlation of the Tills of Northeastern Ohio by Size Analysis .... *V. C. Shepps* 34

A Method for the Size Analysis of Sand on a Number Frequency Basis ..... *Arthur W. Marschner* 49

NOTES

Transport and Rounding of Large Boulders in Mountain Streams ..... *Maxwell Gage* 60

Para-Ripples in Limestone with Special Reference to Occurrences in the Mississippian Boone Formation ..... *V. O. Tansey* 62

REVIEW

Charles J. Kundert. Geology of the Whittier-La Habra Area, Los Angeles County, California ..... *M. N. Bramlette* 64

16

# Journal of Sedimentary Petrology

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Articles submitted for publication to the *Journal of Sedimentary Petrology* should have a prefatory abstract and sufficient postage should be sent by the author to pay the return of the manuscript as it has been found that many articles require more or less revision before publication.

Persons who are not members of the Society of Economic Paleontologists and Mineralogists or are not subscribers to the *Journal of Sedimentary Petrology* but who desire to publish an article in the *Journal*, should have some member of the Society of Economic Paleontologists and Mineralogists or some member of the American Association of Petroleum Geologists sponsor the article. Members of these Societies are given preference in publication.

Among papers to appear in forthcoming issues of the *Journal* are the following:

A new roundness scale for sedimentary particles. By M. C. Powers.

Weatherability of zircon. By Dorothy Carroll.

Estimation of error in grain size analysis. By J. C. Griffiths.

Beachrock in south Florida. By R. N. Ginsburg.

Clay minerals in the type section of the Morrison formation. By W. D. Keller.

A nomogram for obtaining percent composition by weight from mineral grain counts. By Robert Berman.

Petrology of the Spraberry sands. By G. F. Warn and Raymond Sidwell.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 23, NO. 1, PP. 3–9
FIGS. 1, 2, MARCH, 1953

# ILLITE AND MONTMORILLONITE IN GREEN SEDIMENTARY ROCKS

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University of Missouri, Columbia, Missouri

## ABSTRACT

The green constituents of ordinary sedimentary rocks are present commonly in the clay-sized fraction. They were identified in representative green sedimentary rocks as members of the illite and montmorillonite clay mineral groups.

The nature of combination of both ferric and ferrous iron should be recognized when relating iron and mineral color. Ferric silicates in sedimentary minerals are greenish, whereas ferric oxides are red, yellow, and brown.

## INTRODUCTION

The green constituent in greenish shales, clays, and other sedimentary rocks is rarely defined mineralogically in published descriptions of those sedimentary rocks. Commonly the source of the green color is not mentioned, but occasionally it may be ascribed with qualification to, "possibly chlorite or glauconite," or more vaguely as "due to ferrous iron."

Red, yellow, and brown colors in sedimentary rocks are known with certainty to be due to iron oxides (more or less hydrated); black is due to carbon, iron sulphide, or manganese oxides; white to reflection from many tiny surfaces of finely divided, essentially colorless particles, and intermediate colors to mixtures of these materials. Furthermore, that colors of minerals vary with particle size, index of refraction of the surrounding medium (as when wetted), polarization, diffraction, scattering, and other causes has been discussed most ably by Kennard and Howell (1941).

To sharpen our recognition of the green constituents of the common sedimentary rocks a variety of them were examined in some detail in this study. The source of the green color in rocks containing coarse-grained glauconite, large fragments of clastic chlorite, more or less altered greenish biotite, or malachite stain is too obvious to need mention. Less obvious, however, is the nature of the finely divided greenish pigment in some limestones, sandstones and siltstones, and in shales. It soon became apparent after careful examination of the rocks that the green color in limestones could be concentrated in the fine, argillaceous, acid-insoluble residue of the limestone, and that the green color in siltstones and sandstones is commonly due likewise to a clay-sized coating or interstitial filling. Consequently the search for the identity of the green substance was narrowed to a determination of the green clay mineral present in the rock.

## FOUR REPRESENTATIVE GREEN ROCKS

Although numerous other samples were studied, four selected specimens of green sedimentary rocks will be reported on because they represent large groups of the common sediments.

1. A green, non-marine sandy clay. The Morrison formation of the Rocky Mountain region is distinguished for its outstanding variegated colors. Because various shades of green are commonly displayed in this formation it should be included in a study of green sediments. Moreover, the Morrison can be classified with confidence as a non-marine sedimentary deposit. A green sample taken about 50 feet above the base of the Morrison from its exposure in the desert, 13

miles east and 7 miles south of Green River, Utah, is illustrative of the green Morrison.

It is a grayish-green sandy clay (between 10 G Y 5/2 and 5 G 5/2 in the rock color chart, National Research Council, 1948). Feldspar is abundant among the coarser particles, and quartz, biotite, and muscovite occur in lesser quantity. Presumably the sandy clay is a partially altered volcanic ash, although no shards were visible in this specimen. The fine clay fraction, less than 2 microns in equivalent settling diameter, gives a strong clear-cut, X-ray diffraction pattern of montmorillonite (approximately 18 Å interplanar 001 spacing when solvated with ethylene glycol), with a small amount of illite (or primary muscovite). Chloritic clay was not indicated (see fig. 1). It is concluded from this specimen, and confirmed by other identifications of montmorillonite in the Morrison, that green color in clay arises from montmorillonite.

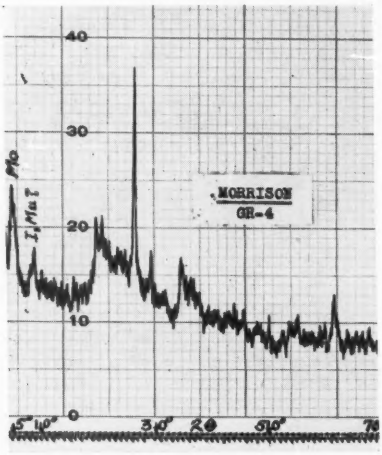


FIG. 1.—X-ray diffraction spectrogram of Morrison green clay from near Green River, Utah. The peak at approximately 5° (2 $\theta$) or 18 Å basal interplanar spacing indicates montmorillonite (Mo) solvated in ethylene glycol. Illite (I), or perhaps residual primary muscovite (Mu), register a 10 Å or 9° peak. The back-ground climbs quickly from 3° (2 $\theta$) downward because the main beam of the X-ray is approached closely. Ni-filtered Cu radiation, Norelco spectrometer.

It is not to be construed that all green clays in the Morrison, or even that all clays in the Morrison are necessarily montmorillonite; the section at its type locality (Waldschmidt and Leroy, 1944) may be zoned on sequences of kaolinite, illite, and montmorillonite (manuscript in preparation). However, much of the greenish clay in the Morrison is montmorillonitic.

Recently Sudo, *et al.* (1952), reported on four green montmorillonites resulting from the alteration of tuffaceous and volcanic rocks. Their No. 2 montmorillonite, from Oya, Tochigi Prefecture, "is green when unoxidized. In daylight, however, it turns gray to black and finally to brown" (page 125). Grim (1951) noted that "montmorillonite may be white, yellow, red, green, or gray, depending on its composition."

2. A green-spotted siltstone. The red beds (Spearfish, Chugwater, Chinle, Moenkopi and others) of the Rocky Mountain region commonly contain green spots or larger blotches surrounded by the characteristic red-bed color. The red color derives from a coating of ferric oxide on the sand, silt, and clay particles. If the ferric oxide is reduced by $H_2S$, and then dissolved by carbonate water (both naturally occurring reagents), the rock displays a pale, gray-green color (Keller, 1929). The green color was not due to the reduced iron compound which was dissolved away, but the green substance manifested its color when the previously masking ferric oxide was gently removed. Presumably the green substance had been present all along, but had been hidden by the stronger red ferric oxide pigment.

In the present investigation, a considerable quantity of such green-blotched (between 10 G 8/2 and 6/2) siltstone was taken from within surrounding deep red, clayey, texturally-similar siltstone from the Chugwater formation at Circle Ridge Dome, T. 6 N., R. 2 W., Fremont County, Wyoming. The green rock was disaggre-

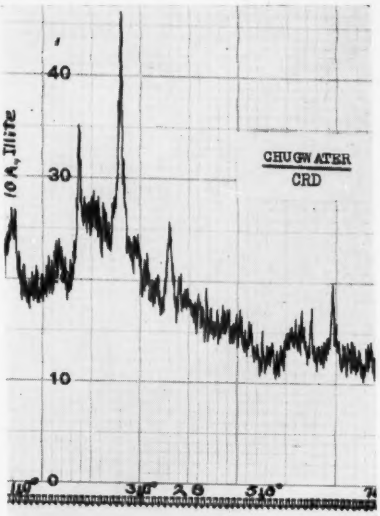


FIG. 2.—X-ray diffraction spectrogram of clay from Chugwater green spot, Circle Ridge Dome, Wyoming. The peak at approximately 9° (2 $\theta$), 10 Å indicates illite. Some quartz is present in the specimen. Ni-filtered Cu radiation, Norelco spectrometer.

gated and the clay fraction (less than 2 microns in equivalent settling diameter), which carried the green color, was separated for study and mineral determination.

A differential thermogram of the clay shows endothermic peaks at 170°, 600°, and 870°C. and one exothermic peak at 910°C. The X-ray diffraction pattern shows a strong reflection at 10 Å unresponsive to ethylene glycol (see fig. 2). The green clay is ordinary illite, but not glauconite within the illite group, as may be seen from the chemical analysis in table 1. Glauconite would have been higher in iron and lower in aluminum. There is no X-ray evidence of a chloritic clay mineral.

Robb (1949) found illite to be "the only mineral present" (p. 101) in a sample from a green micaceous shale associated with red shale in the Permo-Pennsylvanian Maroon formation in mid-western Colorado. Grim (1951, p. 231) wrote that "illite is green, yellow, or black; as far as the writer known, no red illite has been found." The red-stained clay in the Chugwater adjacent to the green also gives an illite diffraction pattern, but the red color is presumably due to mechanically incorporated ferric oxide. One wonders if red montmorillonite (see Grim, 1951; Sudo, *et al.* 1952) may not owe its red color also to ferric oxide which is held externally to the clay crystal lattice.

It is not intended to suggest that the color of the red beds is due to an oxidation process of the iron in the clay, analogous to the turning brown of Sudo's, *et al.* (1952) clay by oxidation. It seems more probable that the source of red bed sediments was red, well-oxidized soil.

It is concluded from the identification of the green clay fraction in the Chugwater siltstone that the green color arises from the illite present.

3. A green clay associated with dolomite. Green partings, green clay concentrates, and a greenish tinge are not uncommon among limestones. Such a green (between 5 G 7/2 and 5/2) clay was collected from the Ordovician Jefferson City formation of Missouri at NE¼ SW¼ SE¼ sec. 35, T. 46 N., R. 8 W., (Hambleton, 1952). This clay represents a green parting and probably also a natural concentration of an insoluble residue of the limestone at the contact with the St. Peter sandstone. It is thought to be responsible for the green tinge commonly seen in some beds of the Jefferson City formation.

The fine fraction (less than 2 microns) which was separated from the coarser quartz silt gave a differential thermogram with endothermic peaks at 150°, 660°, and 900°C., and an exothermic peak at 940°C. It showed a strong X-ray reflection at 10 Å, unresponsive to ethylene glycol. Again, the green clay is illite, and not glauconite (see analysis 2 in table 1). No evidence of a chloritic clay mineral was seen. Hence, the green clay in dolomite may be illite.

TABLE 1.—*Chemical analyses of green and related clays*

| | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| $SiO_2$ | 47.35 | 52.83 | 50.47 | 40.54 | 51.22 |
| $Al_2O_3$ | 20.05 | 20.00 | 23.82 | 5.19 | 25.91 |
| $Fe_2O_3$ | 2.78 | 3.54 | 5.15 | 31.24 | 4.59 |
| FeO | 0.29 | 0.46 | 0.50 | 0.39 | 1.70 |
| MgO | 2.40 | 2.87 | 1.83 | 0.06 | 2.84 |
| CaO | 3.78 | 1.03 | 0.48 | 1.92 | 0.16 |
| $Na_2O$ | 0.17 | 0.13 | 0.15 | 0.14 | 0.17 |
| $K_2O$ | 4.31 | 6.52 | 6.83 | 0.24 | 6.09 |
| $TiO_2$ | 0.43 | 0.10 | 0.38 | | 0.53 |
| $P_2O_5$ | 0.08 | 0.42 | 0.32 | | |
| $H_2O$-105° | 5.36 | 3.22 | 2.06 | 6.00 | |
| Loss above 105° | 12.98 | 8.84 | 7.96 | 14.75 | 7.49 |
| Total | 99.98 | 99.96 | 99.75 | 100.47 | 100.70 |

1. Clay size fraction of green siltstone from Chugwater formation, Circle Ridge Dome Wyoming. Probably some fine particles of dolomite from the cement in the siltstone have contributed to the CaO, MgO, and loss above 105°C.
2. Clay size fraction of a green clayey residue in the Jefferson City dolomite, sec. 35, T. 46 N., R. 8 W., Callaway County, Missouri. Probably a small amount of dolomite in the clay has contributed to the CaO, MgO, and loss above 105°C.
3. Clay size fraction of the green lower clay in the Loutre formation, Mexico, Mo., pit of the A. P. Green Fire Brick Company.
4. Nontronite, Manito, Washington, API Reference Clay No. 33 b. (API, Prelim. Rpt. 7, 1950, p. 55).
5. Illite, fine colloid fraction, near Fithian, Ill. Analysis No. 2 from Grim, Bray, and Bradley, 1937.

Analyses 1–3 by the Bruce Williams Laboratories, Joplin, Missouri.

4. A green-colored representative of the clay and clay-shale group of sediments was chosen from the lower clay in the Pennsylvanian Loutre formation (McQueen, 1941, p. 71), collected where it overlies the fire clay in the strip pit of the A. P. Green Fire Brick Company, Mexico, Audrain County, Missouri. The clay is plastic and grayish yellow green (between 5 G Y 7/2 and 5/2).

The differential thermogram and X-ray diffraction pattern give clear-cut identification of illite. No reflections of chlorite, kaolinite, or montmorillonite are shown in the X-ray pattern. The chemical analysis, no. 3 in table 1, is indicative of illite.

## SUMMARY

The green color in many common sedimentary rocks lies in their clay mineral constituents. The green clay mineral which is found to be common in marine sedimentary rocks is illite. Green montmorillonite is abundant in the non-marine Morrison. Perhaps this montmorillonite would have been altered to illite if it had been transferred to a marine environment (Millot, 1949; Grim 1951).

Chloritic clay mineral was not observed in the green clays herein reported on. It is possible that further fractionation of the clay samples might have isolated detectable quantities of it, but there is no evidence that chlorite is necessary for a green color in clay.

The green illite found does not have the bulk chemical composition of glauconite.

## ADDITIONAL COMMENTS ON COLORED MINERALS IN SEDIMENTARY ROCKS

The green color in sedimentary minerals is apparently related to the presence of iron in them and the nature of its combination.

MacCarthy (1926) who studied rather thoroughly the colors of minerals with

special emphasis on the clays and other sediments, concluded (p. 17) that "aside from organic colors and an occasional clay tinted with manganese, iron compounds of one sort or another seem to be almost solely responsible for these colors." He correlated with moderate success the colors of iron-bearing minerals with their $FeO/Fe_2O_3$ ratios and degrees of hydration. Some anomalies appear in the appl.cation of his scheme which was based on molecular chemistry. Probably a sounder correlation will be forthcoming when sufficient data are accumulated to relate the crystal chemistry of the iron compounds to their colors. Currently these data appear inadequate.

Nevertheless, the common iron-bearing sedimentary minerals are usually characterized by certain colors, and their relations and contributions to the colors of sedimentary rocks may be summarized in terms of constituent iron compounds as below.

1. Ferrous oxide, FeO. The "mineral" wüstite, FeO, is artificially prepared, and is not known in sediments. It is incorrect therefore to ascribe the green color in sedimentary rocks to ferrous oxide, *per se*, as has sometimes been done.

2. Ferric oxide, including the hydrated forms, may occur in several minerals:

Hematite, $Fe_2O_3$, red, purplish red, and possibly but improbably gray in sediments.

Goethite, $HFeO_2$, yellowish, brownish, less commonly reddish. Goethite is a major, usually dominant constituent of limonite.

Lepidocrocite, FeO(OH), is red, orange, brownish. Lepidocrocite is also a constituent of limonite. Hofer and Weller (1947) report that the oxidation of $Fe(HCO_3)_2$ solutions with low $CO_2$ concentration favors the formation of lepidocrocite.

Maghemite, or gamma ferric oxide (van der Marel, 1951), $Fe_2O_3$ (magnetic hematite with the structure of magnetite), is red and brown. Red maghemite may invert to red hematite according to Hofer and Weller (1947).

Limonite includes the hydrous iron oxides which give a yellowish to brownish streak. Although limonite is not a mineral name it is a useful term which is non-committal of the individually non-identified iron oxides. See goethite and lepidocrocite.

According to Kennard and Howell (1941, p. 411) ferric oxide is markedly polychromatic. "For example, with decreasing particle size hematite may change in color from nearly black to red (which is the color of the streak), and finally to yellow (which is also the color of solutions of ferric iron)." Hematite-goethite relationships are discussed by Smith and Kidd (1949).

3. Ferro-ferric oxide, $Fe_3O_4$, magnetite, gray to black.

4. Iron silicates which are green or greenish in color include several minerals:

Montmorillonite, when probably iron-rich.

Nontronite, which contains mainly ferric iron and little aluminum in the octahedral layer. See analysis no. 4, table 1. All of the iron has been assigned to the octahedral layer ($Al_{.03}Fe_{2.02}Mg_{.005}$). This clay is bright yellowish green.

Illite. Perhaps the iron content must exceed a threshold quantity to appear green, but if so the limits are not known.

The intensity of the green color rises in the samples following the sequence 1–4 of the analyses in table 1, wherein the ferric iron (not the ferrous iron) content rises in the same order. Fithian, Illinois, illite (analysis 5) which has been seen by the writer is grayer, and never as green as the samples 1–4, although its ferric iron content is intermediate within the group. However, a small amount of finely divided carbon, which has high pigmenting properties, could cover completely a pale, recessive green color, and leave the clay gray.

In the same manner, a slight amount of strongly colored ferric *oxide* can stain clay red. Robb (1949) suggested as a source of hematite in the mica, the oxidation of iron from the center (octahedral) sheet in its crystal structure.

Special emphasis should be given to the fact that the *oxide* of ferric iron is red to brown, whereas a *silicate* which contains ferric iron may be green. Quite probably the green-exciting vibrations arise because of the bonding and position of the iron in relation to silica tetrahedra. Valence is probably of less consequence than coordination and nearest neighbors in the production of color. Epidote, amphiboles and pyroxenes may vary greatly in their ferric-ferrous ratio and still be green. Although the conventional chemical analysis of any green silicate (illite or nontronite) reports the iron in the oxide form ($Fe_2O_3$ and FeO), actually and mineralogically the iron is combined as a silicate.

There is little excuse for confusing the two combinations of ferric iron (oxide and silicate) or for misinterpreting analytical reports. However, teaching experience has well demonstrated to the writer that too many college students in geology who "took and passed" required chemistry courses resisted assimilation of their subject matter to the extent that ferrous and ferric, oxides and silicates, are disappointingly strange to them. It is hoped that this reminder may point up the value and necessity of keeping one's thoughts straight on iron compounds in the sedimentary minerals.

Chloritic clay mineral. A chloritic clay mineral which is characterized by a basal interplanar spacing of about 15 Å is widespread but not always abundant in argillaceous sediments. Its physical properties have not been described in the literature, and its contribution to green color in sediments can not now be evaluated.

Glauconite, celadonite, and non-sedimentary chlorite, commonly occur in silt-size and larger particles whereby they are readily recognized.

Iron sulfide minerals include pyrite and marcasite, $FeS_2$, and melnikovite, which has an indefinite composition near FeS. All of these minerals impart a black, or dark greenish-black color to clays.

Ferrous silicate, aluminate, and borate compounds, in general artificially prepared, are colorless to blue (Bancroft and Cunningham, 1930; Spring 1898). Special care must be taken in their preparation to prevent even slight oxidation, or the colors become progressively green and then yellow. Bancroft and Cunningham (1930), MacCarthy (1926), and Kennard and Howell (1941) point out that a mixture of blue and yellow compounds will produce green colors. The writer believes that a sounder explanation of the color mechaism will lie in the crystal chemistry of the iron-bearing compounds.

## CONCLUSIONS

The green color in most common sedimentary rocks arises from the illite and montmorillonite clay mineral groups. Ferric iron accompanied by ferrous iron, within a silicate framework characterizes green minerals. It is suggested that coordination within the silicate lattice is of greater moment in the production of a green color than the valence of the iron. Ferric iron oxide is red, yellow, or brown, varying in color with particle size and degree of hydration. Ferrous oxide, *per se*, is not a mineral constituent of sedimentary rocks.

## ACKNOWLEDGMENTS

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Shortly before galley proof for this article was read, late papers by W. A. Weyl, "Light absorption as a result of two states of valency of the same element," and by R. R. Shively, Jr., and W. A. Weyl, "The color change of ferrous hydroxide upon

oxidation" (Journal of Physical and Colloid Chemistry, vol. 55, 1951, pp. 507–512, and 512–515, respectively) were found which shed light on the problem. Electron transfer effective over a considerable distance, as the order of ten atomic diameters, between cations of one element with two valencies, as $Fe^{2+}$ and $Fe^{3+}$, results in an oscillation of valency which accounts for intensive light absorption, and therefore for the ensuing color of the iron-containing substance. The partial oxidation of FeO to $Fe_2O_3$ gives rise to a blue color, as in vivianite an iron phosphate, and in artificially prepared iron hydroxides. Blue plus yellow (ferric oxide) pigments blend to give a green color. The green color of iron-bearing minerals arises then from the combined presence of both ferrous and ferric ions. Hydrated ferro-ferric minerals tend toward green, whereas anhydrous compounds tend toward gray and black. These findings are pertinent and supplementary to the writer's comments on the colors of iron-containing minerals.

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FIGS. 1, 2, MARCH, 1953

# ANALCIME IN THE CHINLE FORMATION OF UTAH CORRELATIVE WITH THE POPO AGIE OF WYOMING

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## ABSTRACT

Analcime occurs in a zone at least 12 feet thick in the upper part of the Chinle formation on the south flank of the Uinta Mountains near Vernal, Utah. The presence of analcime in this stratigraphic position and its association with an ocherous lithology permit correlation of this zone with the Popo Agie member (Chugwater formation) of Wyoming. Contemporaneity and similar environment of deposition are indicated by the analcime beds.

## INTRODUCTION

The occurrence of analcime as a significant and distinguishing mineral constituent of the Popo Agie member of the Chugwater formation was reported in an earlier paper (Keller, 1952). It was also pointed out that stratified analcime might be used as a geological time zone marker. A later find of ocherous, analcime-containing beds in the rocks assigned to the Chinle formation on the south flank of the Uinta Mountains is therefore of stratigraphic interest, because the analcime bearing zone serves to correlate on firm ground the upper part of this Chinle in the Uinta Mountains with the Popo Agie of the Wind River (Wyoming) Mountains. Since the Triassic red beds of the western United States lack good fossil markers, other means of correlation become more welcome.

## ANALCIME IN THE CHINLE NEAR VERNAL, UTAH

Sedimentary formations dip gently outward on the south flank of the Uinta Mountains in Utah. Cover is sparse over much of the area and rocks from the pre-Cambrian to Tertiary are bared to view in a magnificent manner. The stratigraphic sequence is apparent even to a non-geologist driving along Utah State Highway 44 which connects Vernal and Manila, Utah. Untermann and Untermann (1949) have capitalized on the unsurpassed stratigraphic exposures as geologic exhibits by erecting along the highway, near formation boundaries, sign posts which identify the formations exposed. They have carried formation names northward from the geologically prominent areas and type sections in southern Utah and Arizona. This stratigraphic nomenclature is endorsed by a majority of the many oil company and U. S. Geological Survey geologists working in the area (oral communication from G. E. Untermann, 1952).

The Chinle formation, identified on the above basis, is well exposed about 10 miles north of Vernal where Utah 44 crosses the dipping outcrop (see fig. 1). It is overlain by the prominent, massive, cross-laminated Navajo sandstone. The upper part of the Chinle here is ocherous in color, and weathers to sandy and gravelly slopes similar to the Popo Agie member in Wyoming. It was the close similarity in general appearance to the Popo Agie, and therefore the suspected possible occurrence of analcime, which prompted the writer, while hurriedly passing through the area, to collect samples from the near-at-hand Chinle outcrops. A comprehensive study of the Chinle was not possible due to lack of time in the field but samples were taken which were representative of the several color and lithologic zones near the top of the formation. These samples have been carefully stud-

FIG. 1.—Outcrop of the ocherous, analcime-containing upper part of the Chinle formation on Utah State Highway 44 about 10 miles north of Vernal, Utah. Note marker sign erected by the Untermann's, which is one of those calling attention to each stratigraphic formation along the highway.

ied in the laboratory by the usual petrographic techniques, including X-ray diffraction.

In descending order, the lithologic and color zones were sampled as follows. Approximate thickness only is given for the zones because they vary and intergrade within short lateral distances.

Navajo sandstone. Typically tan, massive, cross-laminated.

Chinle formation. Red, 5 R 6/2 to 4/2, silty (quartz) shale, weathers to tiny angular fissile fragments. Contains both dolomite and calcite. 6′–8′ ±

Light yellowish brown shale, between 10 Y R 6/2 and 5/4 shale. Otherwise similar to red zone above. 3′–4′ ±

Pinkish-gray, near 5 R 7/2 to 9/2, ocherous silty marl (calcareous). Weathers with a yellowish powdery coating. 10′ ±

*Grayish yellow, 5 Y 7/4, ocherous, calcareous silty clay, with associated harder, resistant brownish, 10 Y R 5/4 masses. The harder material contains analcime, calcite, and dolomite. Oolitic texture is poorly developed. 3′–5′ ±

*Yellowish brown, 10 Y R 6/4, nodular, hard limestone containing analcime. Broken with many intersecting white to light tan carbonate veins. 3′ ±

*Light brown, 5 Y R 6/4, ocherous, silty, slightly oolitic, fine-granular analcime rock. 3′ ±

*Reddish brown, near 10 R 3/4, matrix with abundant fine, light-colored oolites and sand-silt grains. The light colored material is analcime. See figure 2. Base of this zone is covered by talus. 5′ ±

* An asterisk marks the analcime—containing beds.

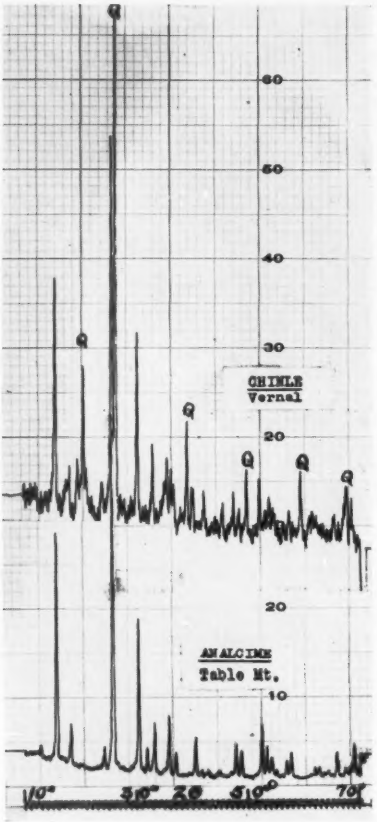


FIG. 2.—X-ray diffraction spectrogram showing reference, pure analcime from Table Mountain (Golden) Colo., and the Chinle sample from near Vernal, Utah. Note that all analcime peaks are shown in counterpart in the Chinle sample, plus peaks from quartz (Q), which develops notably strong X-ray reflections and iron-oxide background reflection and fluorescence. Ni-filtered Cu radiation on a Norelco spectrometer.

## BASIS FOR CORRELATION

It is seen from the description above that some 12 to 15 feet of the Chinle section beginning about 20 feet below the Navajo contains in an ocherous lithology, analcime which was deposited presumably on a single, wide-spread floor. However, through the course of geological investigation the single, unique, but unrecognized analcime zone has been placed within two different formations, the Chinle and Popo Agie. The analcime now serves to tie together in time of deposition a zone occurring in the red beds of Wyoming (Chugwater) and a zone occurring in the red beds of northern Utah and extending south, the two regions being separated structurally by the Uinta uplift.

Previous mention has been made of the close similarity between the appearance of the Chinle-Navajo boundary rocks in the Vernal locality, and the Popo Agie-Nugget (Wyopo) boundary in the Lander, Wyoming area. They are so nearly alike that if one had been working on the Popo Agie-Nugget (Wyopo) contact, and then had been transferred to the Utah area without knowledge of the Chinle-Navajo terminology he would without much hesitation apply the former names. The thick, massive, highly cross-laminated, "clean" Navajo and Nugget sandstones are notably similar in superficial appearance, which supports the view that they are parts of a single depositional sheet and are correlative, their current stratigraphic status.

## ACKNOWLEDGMENT

It is a pleasure to acknowledge financial aid from the University of Missouri Research Council Grant No. 444 toward a trip on which this research material was collected.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 23, NO. 1, PP. 13–17
FIG. 1, MARCH, 1953

# EVIDENCE OF BIOCHEMICAL HEATING IN LAKE MEAD MUD[1]

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## ABSTRACT

Soft sedimentary material is rapidly accumulating on the bottom of Lake Mead in back of Hoover Dam across the Colorado River. The temperature of this sediment increases sharply with depth in the topmost layers, below which lower temperatures have been recorded with a special penetrating bathythermograph.

Bacterial thermogenesis appears to be responsible, at least in part, for the higher temperatures found in the sediment. Millions of living bacteria per gram were found in Lake Mead mud, the largest populations occurring in the topmost layers where the thermocline is steepest. Assuming that the bacteria generate heat at an average rate of $30 \times 10^{-12}$ calories per cell per hour, ten million might generate 2.6 calories in a gram of mud in a year.

Increases of a degree or more in temperature were noted in Lake Mead mud samples incubated for 20 days in thermos bottles, but little or no change occurred in similar mud that had been sterilized by autoclaving.

Oxygen and utilizable organic content affect the biochemical heating of mud.

## INTRODUCTION

Lake Mead, formed by Hoover Dam across the Colorado River on the Arizona-Nevada border, is rapidly filling with sediment (Gould, 1951). Bathythermograph tracings have revealed anomalous temperature gradients in the sediment. At the bottom of the lake where the bathythermograph entered the mud, there appeared to be a sharp temperature increase, which at certain stations was as much as 9°F. within the first five feet of penetration (Anderson and Pritchard, 1951).

Figure 1 shows a temperature-depth tracing made mid-channel a short distance upstream from Hoover Dam on 22 December 1948. During the descent of the bathythermograph, especially designed to penetrate the soft mud to a depth of nearly 100 feet, it registered temperatures increasing from 52.6°F. at the water surface to 53.8°F. at the mud-water interface. As the instrument entered the mud the temperature increased sharply within the topmost few feet. After reaching a maximum of 58.8°F. at a mud depth of about 30 feet, the temperature decreased with further penetration. The record made during the return of the instrument to the surface is probably in-

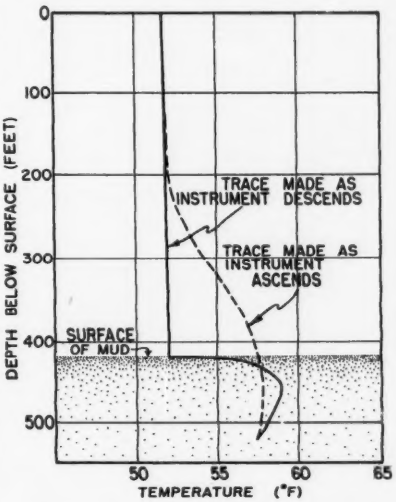


FIG. 1.—Bathythermograph tracings indicating heating in topmost few feet of Lake Mead mud.

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fluenced by the insulating effect of mud clinging to the thermal element; hence, it does not coincide with the descending record.

Neither heat conduction from the earth nor radioactivity seems to account for the sharp temperature increase near the mud surface. Therefore some consideration has been given to the possibility that heat generated by biochemical reactions catalyzed by bacteria in the mud may be partly responsible. Biochemical heating commonly occurs in compost piles, manure heaps, fermenting silage, and incompletely dried hay or grain (Miehe, 1911; James *et al.*, 1928; Gilman and Barron, 1930; Wedberg and Rettger, 1941). Many creatures in nature take advantage of heat generated by bacteria in decomposing materials to give increased temperatures favorable for the incubation of their eggs or offspring.

### BACTERIAL POPULATION OF MUD

Samples were collected mid-channel from fifty to a hundred yards upstream from Hoover Dam by means of a modified Ekman sampler. The apparatus consisted essentially of a plastic cylinder 30 inches long and two inches in diameter rigged to penetrate the mud in a vertical position with both ends open. It was lowered from a boat equipped with a cable and winch. When the desired depth was reached, a heavy messenger sent down the cable activated a mechanism that simultaneously closed both ends of the plastic cylinder with rubber stoppers. Water as well as semi-fluid mud samples were collected with this apparatus.

Within an hour after their collection, several samples serially diluted with sterile water were introduced into nutrient media in a field laboratory at Boulder City. It was necessary to complete the bacteriological analysis of the samples at La Jolla a day or two after their collection. In order to minimize changes in the microflora that may occur in such samples during storage (ZoBell, 1946) they were held at about 40°F. The inoculated media were incubated at 82°F. for 20 days, after which they were examined for evidence of bacterial growth or physiological activities of various kinds in selective media.

The abundance of bacteria was estimated by the extinction dilution method, a procedure in which 1.0 gram of inocula, or dilutions thereof by powers of ten, were introduced into appropriate nutrient media. The reciprocal of the log of the lowest dilution that showed signs of bacterial activity was assumed to represent the most probable number of active organisms. For example, when bacterial growth occurred in duplicate tubes of nutrient medium inoculated with 1.0, $10^{-1}$, $10^{-2}$, or $10^{-3}$ grams of a given sample but no growth in similar medium inoculated with $10^{-4}$ grams of the same sample, it was assumed that the sample contained a

TABLE 1.—*Bacterial growth, indicated by plus sign (+), or lack of growth (−), in nutrient medium inoculated in duplicate (a and b) with diminishing amounts of water or mud from different depths below the mud-water interface at the bottom of Lake Mead*

| Amount of inocula | Water sample from surface | | Mud from 0.3 feet | | Mud from 46 feet | | Mud from 99 feet | |
|---|---|---|---|---|---|---|---|---|
| grams | a | b | a | b | a | b | a | b |
| 1.0 | + | + | + | + | + | + | + | + |
| $10^{-1}$ | + | + | + | + | + | + | + | + |
| $10^{-2}$ | + | + | + | + | + | + | + | + |
| $10^{-3}$ | + | + | + | + | + | + | + | + |
| $10^{-4}$ | − | − | + | + | + | + | + | + |
| $10^{-5}$ | − | − | + | + | + | + | + | + |
| $10^{-6}$ | − | − | + | + | + | + | + | + |
| $10^{-7}$ | − | − | + | + | − | − | − | − |
| $10^{-8}$ | − | − | − | − | − | − | − | − |

TABLE 2.—*Minimum numbers of various physiological types of bacteria per gram of Lake Mead mud as indicated by extinction dilution method with differential nutrient media*

| Physiological type of bacteria | Mud from 0.3 feet | Mud from 46 feet | Mud from 99 feet |
|---|---|---|---|
| Multiply in peptone medium | $10^7$ | $10^6$ | $10^6$ |
| Liquefy gelatin | $10^6$ | $10^5$ | $10^5$ |
| Hydrolyze starch | $10^3$ | $10^3$ | $10^3$ |
| Decompose cellulose | $10^2$ | $10^2$ | $10^3$ |
| Reduce nitrate to nitrite | $10^6$ | $10^5$ | $10^4$ |
| Reduce sulfate to sulfide | $10^3$ | $10^2$ | $10^4$ |
| Oxidize $H_2$ | $10^2$ | $10^2$ | $10^4$ |
| Ferment glucose | $10^7$ | $10^5$ | $10^5$ |

minimum of $10^3$ or 1000 bacteria per gram that grew in this particular medium. Similarly, as summarized in table 1, growth in the $10^{-6}$ or $10^{-7}$ dilutions of mud showed that these samples contained a minimum of $10^6$ or $10^7$ viable bacteria per gram respectively. That such estimates are minimal is stressed, because it is unlikely that any one medium could provide for the growth of all bacteria that might be present.

Not only were large bacterial populations found at all levels in the lake mud but also detected were physiological types that could attack several different kinds of organic and inorganic substances (table 2). Aerobic bacteria predominated in the topmost layers of mud where free oxygen and food were most plentiful. Most of the aerobes detected in deeper strata proved to be facultative forms whose activity must have been anaerobic *in situ*. From cumulative results, including direct microscopic counts that are generally from ten to a hundred times higher than cultural counts, it is estimated that the topmost layer of Lake Mead mud contained bacterial populations of the order of $10^7$ to $10^8$ cells per gram.

Based on the assumption that physiologically active aerobic bacteria, of the types commonly occurring in lakes, generate heat at an average rate of $30\times10^{-12}$ calories per cell per hour, $10^7$ bacteria in a gram of mud might generate heat at a rate of $30\times10^{-5}$ calories per hour. Multiplying this value by 8760, the number of hours in a year, gives 2.6 calories per year as the amount of heat generated by $10^7$ bacteria in a gram of mud. At this rate a bacterial population of $10^8$ bacteria would generate 26 calories per gram of mud per year. Although these values may be only probable orders of magnitude owing to many variable and some unknown factors that affect heat generation by bacteria, the calculations indicate that, in a well insulated system such as mud, bacteria could account for the rise in temperature recorded by the bathythermograph in the topmost few feet of mud (fig. 1).

The value $30\times10^{-12}$ calories of heat generated per bacterial cell per hour is believed to be conservative. It is derived from the data of ZoBell (1940a, b) on the rate at which organic substances occurring naturally in lake and sea water are oxidized by bacteria, the average rate being $20\times10^{-12}$ mgm per cell per hour at 78°F. The rate may be ten to a thousand or more times as high for higher concentrations of more readily utilizable organic substances than ordinarily occur in lake or sea water. The complete oxidation of a milligram of a hexose (which may be regarded as a representative organic substance for purposes of calculating heat production) yields 3.7 calories. However, experiments on oxygen uptake and $CO_2$ formation indicate that only about half of the theoretical heat of combustion of such substances oxidized by bacteria is liberated as heat, the remainder being used in other vital reactions, including the synthesis of bacterial cell substance. Assuming that 40 per cent of the theoretical heat of combustion of substances oxidized by bacteria is dissipated as heat, we arrive at a value of $29.6\times10^{-12}$, or in

round numbers $30\times10^{-12}$, calories liberated as heat per bacterial cell per hour.

Carlyle and Norman (1941) noted temperature increases ranging from 0.7 to 9.0°F. per hour in their experiments with decomposing straw in Dewar flasks. From their data on bacterial populations we calculate that their aerobic bacteria genrated heat at an average rate of $12\times10^{-7}$ calories per cell per hour.

### THERMOS FLASK EXPERIMENTS

Several gallons of mud from the lake were collected for experiments designed to measure microbial thermogenesis under carefully controlled conditions. Part of the mud was sterilized by autoclaving and the remainder of the raw mud was stored in a refrigerator until needed. Then, after permitting the mud to come to equilibrium with the temperature at which it was to be incubated, samples were dispersed in quart thermos flasks. Duplicate flasks of the sterilized mud were inoculated with one per cent by volume of raw mud. Following Norman *et al.* (1941), the thermos flasks filled with mud were incubated submerged in a water bath at a temperature approximating that of the mud in order to minimize heat losses. Temperatures were taken with long-stemmed mercury thermometers extending through one-hole stoppers, the bulb being submerged in the mud to a depth midway in the flask. The temperature of the mud was recorded at the onset of each experiment and after different periods of incubation. When incubated in a water bath maintained at 68.0±0.2°F., the temperature of mud containing active bacteria increased from one-half to a degree or more during 20 days (table 3).

The experiment was repeated several times with various modifications, each of which demonstrated some slight degree of microbial thermogenesis. Although providing evidence of biochemical heating, the experiments have little quantitative significance because they do not duplicate conditions existing on the lake floor. Sampling disturbs the mud so that there is increased bacterial activity even at temperatures approximating conditions *in situ*. This may result in temporarily increased thermogenesis followed in stored mud by thermogenesis at a rate lower than on the lake floor, because oxidizable organic matter is consumed without being continuously replenished as it may be in the lake.

TABLE 3.—*Temperature of Lake Mead mud samples after different periods of incubation in quart thermos flasks in a water bath at 68.0±0.2°F.*

| Description of mud | Temperature of mud after | | | Change in 20 days |
|---|---|---|---|---|
| | 0 days | 10 days | 20 days | |
| | °F. | °F. | °F. | °F. |
| Sterile mud (control) | 68.1 | 67.8 | 68.2 | +0.1 |
| Inoculated mud #1 | 68.5 | 68.6 | 69.1 | +0.6 |
| Inoculated mud #2 | 67.8 | 68.1 | 68.8 | +1.0 |
| Raw mud sample #1 | 68.0 | 68.4 | 69.4 | +1.4 |
| Raw mud sample #2 | 68.1 | 68.7 | 69.3 | +1.2 |

The influence of organic content on microbial thermogenesis was demonstrated by enriching mud samples with a chopped preparation of dried algae. The addition of 5 per cent by weight of the material resulted in temperature increases of six to ten degrees in mud incubated in aerated thermos flasks for five days at 68°F. Without aeration the temperature increase was only one or two degrees in five days.

### DISCUSSION

Biochemical oxygen demand (B.O.D.) tests on samples of Lake Mead mud collected from various depths showed little variation in the vertical distribution of biologically oxidizable organic matter,

thereby indicating that most of the organic matter reaching the lake bottom must be oxidized in the topmost layers of mud. Ostensibly being oxidized about as rapidly as it reaches the lake bottom, utilizable organic matter does not accumulate to any appreciable extent, the 20-day B.O.D. values ranging from 247 to 479 parts per million. Significantly, it is at the mud-water interface where the thermocline is sharpest. Available evidence suggests that the temperature increase starting at the mud-water interface is attributable, at least in part, to microbial thermogenesis resulting from the oxidation of organic matter.

Presence of both utilizable organic matter and oxygen appear to be the most important factors affecting microbial thermogenesis. Heat was found to be generated much more rapidly in mud of high organic content through which oxygen was bubbled than in similar mud incubated under anaerobic conditions. Observations on the redox potential of samples from the lake indicated that free oxygen occurs only in the water and in the topmost layers of mud, below which anaerobic conditions prevail.

The microbial oxidation of cornmeal moistened with water in insulated Dewar flasks was found by James (1927) to result in temperature increases up to 9° under anaerobic conditions and as much as 64°F. when aerated with oxygen. Similarly aerated hay heated from an initial temperature of 86° to 143°F., and bacteria in aerated stable manure caused temperature increases exceeding 75°F. (James *et al.*, 1928). Carlyle and Norman (1941) observed biochemical heating in moist oat straw sufficient to cause temperature increases of nearly 90°F.

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FIGS. 1–5, MARCH, 1953

# THE ORIGIN OF THE DEPOSITS OF TUFA IN MONO LAKE

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## ABSTRACT

Deposits of calcareous tufa have formed and are probably forming now in numerous alkaline-carbonate lakes of the western United States. Many of these deposits in the Mono and Lake Lahontan basins are mushroom-shaped and lie at the orifices of what are or were sublacustrine springs. The mushroom-shaped masses are composed of concentrically arranged lithoid, dendritic, and thinolitic tufa with the core usually lithoid and the dendritic and thinolitic layers alternating concentrically outward. The tufa is shown here to be formed as the result of mixing waters of varying calcium and carbonate content which react essentially in accordance with the solubility product of calcium carbonate in distilled water. The thinolitic and dendritic tufas are believed to be the result of either solution and redeposition within the masses or of varying rates of deposition on the outside of the tower. The possibility is presented that many of the deposits of lithoid tufa on the shores of alkaline lakes are formed by precipitation at the contact of rain-wash and lake water.

## INTRODUCTION

During the summers of 1948 and 1949 the author mapped the area east of Yosemite National Park around the western half of Mono Lake, California (fig. 1). On the shore about this part of Mono Lake and in the lake itself are numerous tower-like masses of calcareous tufa and thinolite first described cursorily by LeConte (1879) and subsequently in detail by Russell (1889). Similar masses of tufa are found in alkaline lakes and in fossil lakes in several places in the arid areas of the western United States (King 1878). The origin of tufaceous masses has been variously attributed to algal action, mixing waters, thermal variations, and loss of carbon dioxide. The purpose of this paper is to demonstrate the probable genesis of the Mono Lake tufa "towers" (verifying Russell's hypothesis) and to present a possible origin of the porous coatings of tufa along the shores of numerous alkaline lakes.

FIG. 1.—Location of Mono Lake and other prominent alkaline lakes.

## NATURE AND DISTRIBUTION OF THE CALCAREOUS TUFA

Probably the greatest quantity of tufa around Mono Lake is that present as a thin crust on the Sierran fault scarp which bounds the west side of the lake. The basement rocks comprising the scarp are hornfelsic metasediments ranging in composition from aluminous hornfelses to quartzites and marbles; their trend is parallel to the fault scarp and the western edge of the lake. The tufa is

FIG. 2.—A group of towers of lithoid tufa on the north shore of Mono Lake.

rarely more than a few inches thick but is ubiquitous wherever postdepositional erosion has not cut into the fault scarp. Light gray, tan, to white and very porous, the tufa is rather typical of that found in many parts of the world and is the lithoid tufa described by Russell (1883).

Numerous towers of toadstool-like tufaceous masses ranging from 3 to 15 feet high lie in the lake and on shore along the western and northwestern sides (fig. 2). In the tops of many of the towers in the lake are circular openings up to about 5 feet in diameter from which fresh spring water has issued (Russell 1889). Although the author saw no water discharging from these orifices, springs were found at the bases of several towers on shore (fig. 3), and there is little doubt that many of the craters of the sublacustrine tufas are still springs. Where the beach gravel directly below the towers is exposed, it is cemented by compact tufa.

The tufa comprising the towers in the lake and those towers on shore near the water is very porous and light gray, tan, to white, i.e., the lithoid type like the tufa above the western shore. However, the tufa of the towers which are not at the waters edge is more dense, usually more thinolitic and dendritic; in some places on the underside of overhanging masses it is stalactitic. The thinolite is typical, that is, it consists of irregularily oriented, crystal-like tetragonal pyramids of compact calcite. The dendritic tufa is botryoidal in its external form (fig. 4) and is characterized internally by radial tubular openings (fig. 5).

FIG. 3.—The orifices of a deposit of lithoid tufa at the north end of Mono Lake.

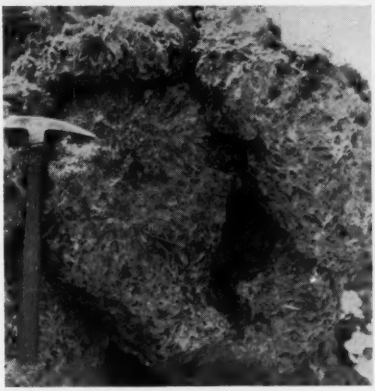

FIG. 4.—Detail of a surface of thinolite.

The three types of tufa writing on the Lake Lahontan occurrences were first

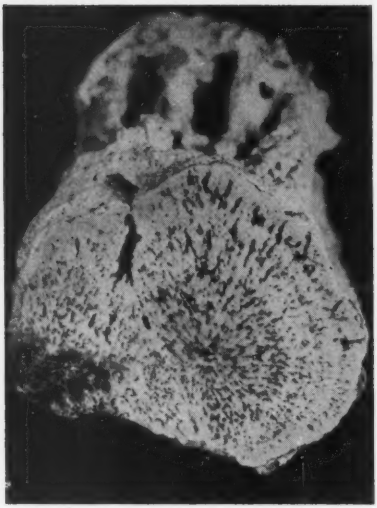

FIG. 5.—Sawed section of a three-inch piece of dendritic tufa.

described by Russell (1883, pp. 189–235). He found that the lithoid tufa occurred generally along the shores as a thick covering and that it was overlain first by the thinolitic and then by the dendritic tufas, the latter being the thicker. The same sequence was present in the towers near the bottom of the lake. He correlated the lithoid stage with a moist climate, the thinolitic with moderate aridity, and the dendritic with the "half full stage," presumably arid. However, no such regularity or correlation was noted in the Mono Lake deposits.

The zoning at Mono Lake is more complex, consisting in one case of a 4-foot core of porous and tubed lithoid tufa, then a 10-inch dendritic layer, a 4-inch thinolitic layer, a 20-inch dendritic layer, a 1-inch lithoid layer and, finally, a 3-inch thinolitic sheath. However, the undissected towers seen in figures 1 and 2 are all lithoid, and the towers seen about 200 feet above the lake level are lithoid at the center and thinolitic outside, the dendritic zone being absent.

One specimen of thinolite, one of porous tufa, and one of dendritic tufa were placed in five per cent solutions of hydrochloric acid and the residues were examined. No carbonate was found in the residue and qualitative tests of the solution gave no reaction for magnesium. The thinolite residue was 1.6 per cent, the porous tufa residue was 0.7 per cent, and the dendritic tufa residue was 3.2 per cent, by weight, all of these having the same proportional values as those found by Russell (table 1). The residue consisted of silt-sized clastic grains and some unidentified organic material. The mineralogy was similar in all cases, i.e., quartz, opal, plagioclase (oligoclase to andesine), epidote, biotite, chalcedony, green hornblende, orthoclase, muscovite, and garnet, the first two being the most abundant. Except for the opal, the minerals are those most common in the meta-

TABLE 1.—*Analyses of tufas from Lake Lahontan*[1]

| Constituents | Lithoid tufa | Thinolitic tufa | Dendritic tufa |
|---|---|---|---|
| Insoluble residue | 1.70 | 3.88 | 5.06 |
| CaO | 50.48 | 50.45 | 49.14 |
| MgO | 2.88 | 1.37 | 1.99 |
| Fe, Al oxides | .25 | .71 | 1.29 |
| $CO_2$ | 41.85 | 40.90 | 40.31 |
| $H_2O$ | 2.07 | 1.50 | 2.01 |
| $PO_5$ | .30 | tr. | tr. |
| Chlorine and sulfuric acid | tr. | tr. | tr. |

[1] By O. D. Allen (Russell, 1883).

morphic and batholithic rocks of the Sierran region on the west side of the lake. The opal is almost as abundant as the quartz and was probably deposited as colloidal silica from the water of the lake. Tufas from Lake Lahontan analyzed by Professor O. D. Allen (Russell, 1883) were also found to consist principally of calcium carbonate, the MgO content averaging about 2 per cent in three analyses (table 1).

Thin sections of the tufa and thinolite

TABLE 2.—*Analyses of water, Mono Lake basin*

| Constituents | Grams per liter | | | | |
|---|---|---|---|---|---|
| | I | II | III | IV | V |
| $SiO_2$ | .0178 | .2800 | .0700 | .07 | .03 |
| Ca | .0414 | .2900 | .0200 | .02 | None |
| Mg | .0044 | .1300 | .0551 | .05 | .03 |
| Li | | | | | .02 |
| K | .0088 | .1600 | .9600 | .95 | 1.29 |
| Na | .0513 | 18.91 | 19.6853 | 19.41 | 20.26 |
| $Al_2O_3$ / $Fe_2O_3$ | | | .0030 | Tr. | .02 |
| $SO_4$ | .0546 | 6.8100 | 6.6720 | 6.58 | 6.93 |
| $PO_4$ | | | | | None |
| $NO_3$ | | | | | None |
| Cl | .0144 | 12.1300 | 12.1036 | 11.95 | 12.46 |
| Br | | | | | None |
| I | | | | | None |
| $B_4O_7$ | | .1600 | .1600 | .16 | .04 |
| $CO_3$ | .0991 | 11.9800 | 13.3903 | 11.98 | 11.26 |
| $HCO_3$ | | | | | 1.73 |
| $H_2O$ (in bicarbonate) | | | .4683 | | |
| Salinity | | 51,850 | 53,473 | 51,170 | 54,074 |
| Density | | | 1.0456 | 1.045 | 1.0443 |
| pH | | | | | 10.3 |

Analysis I: Cold spring water entering Mono Lake at north end (T. M. Chatard).
Analysis II: Mono Lake water, unfiltered (T. M. Chatard).
Analysis III: Mono Lake water, filtered (T. M. Chatard).
Analysis IV: Mono Lake water (T. M. Chatard, 1890).
Analysis V: Mono Lake water, filtered (Edward Goon, Analytical Assistant, Rensselaer Polytechnic Institute).
Analyses I, II, III are from Russell (1889), analysis IV is from Clarke (1924), and analysis V was made for this paper.

showed that the grain size of the calcite ranged from cryptocrystalline to about 0.1 mm., the grains in the thinolite being both the most variable and the coarsest. No tests could be seen in the thin sections; a petrofabric examination of the coarser crystals in two thin sections of thinolite disclosed that the c-axes of the calcite were aligned normal to the elongation of the "prisms" of thinolite.

### WATERS INVOLVED

From the several reported analyses of water of Mono Lake (Russell, 1889 and Anderson, 1887), it is seen that the lime content, which is very important in the explanation of the origin of the tufa towers, is highly variable (table 2). In a paper by Anderson, all the salts were found to be lime salts (analysis not included here); in Russell's analyses the lime varied from 0.29 to 0.02 gram per liter. The lower lime content was from water which had been standing for some time and from which a precipitate had settled. Because the water in Mono Lake is highly alkaline and the laboratory utensils used at the time of the early analyses were probably made of lime glass from which lime could be dissolved by alkaline solutions, it was believed advisable to again analyze the water of Mono Lake. The results are given in column V, table 2. Pyrex glass was used and the water was filtered before analysis. The first analysis in table 2 is of spring water sampled from the orifice of one of the towers in the lake by Russell.

No equipment was available with which to measure the bottom temperatures of Mono Lake, but it may be reasonably assumed that the approxi-

mate average temperature is about 15°C. Although the winters are severe, several thermal springs in the center of the lake probably appreciably raise the temperature of what might otherwise be a very cold lake.

### MODE OF ORIGIN OF THE TUFA TOWERS

In the water of Mono Lake, a solution of some complexity, the ionic constituents do not readily form complex molecules with each other. While it is understood that the value of the solubility product of $CaCO_3$ could be applied only as an approximation, it will be helpful to use this value to explain the conditions which exist. The solubility product of $CaCO_3$ is: $Ca^{++} \times CO_3^{--} = 0.99 \times 10^{-8}$ (15°C) in distilled water (Handbook of Chemistry and Physics, 22nd Edition). If the $CO_3^{--}$ content in distilled water were 11.26 grams or 0.188 mols per liter, the quantity of $Ca^{++}$ which could exist in solution would be about $5.28 \times 10^{-8}$ mols per liter at 15° centrigrade, a quantity not measurable by ordinary analytical methods. Therefore, despite the complexity of the solution in Mono Lake, the fact that no $Ca^{++}$ was found by analysis makes it possible to use the solubility product as a basis for reasoning. Lime is absent not because it is unavailable (the scarp west of the lake is largely of marble) but because it cannot exist in water of the composition found in Mono Lake.

Of additional interest is the extraordinarily high pH value of 10.3 accounting for the fact that comparatively little $CO_3^{--}$ has hydrolyzed to $HCO_3^{--}$. Any appreciable concentration of $Ca^{++}$, either free or as a complex ion, requires that the $HCO_3^{--}$ concentration be high. Also the precipitation of $CaCO_3$ by loss of $CO_2$ depends on a high $HCO_3^{--}$ value.

Three more factors may aid precipitation of lime under the above conditions: (1) the mixing of waters of different temperatures, higher temperatures tending to decrease the solubility of $CaCO_3$; (2) algal action; (3) change in pH.

Algal action may or may not be significant but, on the basis of the other information available, it is certainly not necessary. Furthermore, the comparatively instantaneous precipitation by algae which would be required at the point of contact of the waters would be difficult to explain.

It seems clear that if the temperature of the lake water is higher than that of the springs, as it is during the summer months, lime could be precipitated because of such thermal changes alone. But the change in solubility with change in temperature is not sufficient to cause complete precipitation, for the solubility product at 25°C in distilled water is $.87 \times 10^{-8}$, very near what it is at 15° C.

Change in pH is certainly a factor which facilitates precipitation, but that alone would probably not account for the whole reaction, except in that it is important in the maintenance of a high $CO_3^{--}$ concentration.

The rocks on the west side of Mono Lake are composed largely of marble and, accordingly, spring water entering the Mono Basin from the west should contain appreciable lime. The cold spring water at the orifice of one of the towers did contain lime and, from consideration of the solubility product was found to be approximately saturated with $CaCO_3$. $Ca^{++}$ from the springs entering Mono Lake, where $Ca^{++}$ has been shown to be absent and an improbable constituent, should precipitate immediately at the contact of the two waters as shown by the solubility product. The towers are evidence of this reaction. Such a mode of origin could not have been postulated with any degree of certainty on the basis of the analyses by Chatard, because the spring water contained less $Ca^{++}$ than was shown in his analysis of the water of Mono Lake.

Of particular significance is the large quantity of tufa along the old lake levels of the western shore of Mono Lake. Rainwash and stream water entering the lake from that slope cross thick beds of calcitic marble and would be expected to contain appreciable quantities of

calcium carbonate. It is also reasonable to assume that under these circumstances $CaCO_3$ should precipitate as a thin layer along the shore of the lakes. On the basis of above reasoning and data the author believes that much of the tufa lining the shores of alkaline lakes, which is often attributed to algae or to wave agitation (with loss of $CO_2$), is probably formed as the result of mixing waters.

The question as to why lithoid, dendritic, or thinolitic tufa deposit at particular times remains unsolved. Some of the evidence is contradictory. For instance, the towers seen at the edge of Mono Lake in figure 2 are lithoid and were probably deposited when the water of the lake had its highest concentration of salts. On the other hand, in Lake Lahontan the first and highest deposit formed was lithoid tufa and this was produced when the concentration of salts was probably lowest. In all cases lithoid tufa is the first to be deposited. The thinolitic and dendritic tufas may alternate depending upon the rate of deposition. The relative consistency of the percentages of insoluble material in the three types of tufa from Lake Lahontan and Mono Lake suggest that the rate of deposition decreases from lithoid to dendritic tufa.

Also the external crystalline form of the thinolite still remains a problem. Russell (1889) quoted J. D. Dana who believed that its form was the result of the precipitation of a compound salt of possibly sodium and calcium carbonate, followed by a leaching of the sodium carbonate. Since no such compound is known, such an hypothesis is far from satisfactory but it still presents the only reasonable explanation in the resolution of the problem.

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FIGS. 1–3, MARCH, 1953

# RAFTED PEBBLES FROM THE DEEP OCEAN OFF BAJA CALIFORNIA[1]

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ABSTRACT

Fifty-three pebbles and small cobbles, and several pieces of asphalt, were dredged from the deep Pacific Ocean 60 nautical miles southwest of Cedros Island, Baja California, at a depth of about 2100 fathoms. Thirteen of the rocks are igneous, 12 are metamorphic, and 28 are sedimentary. More than half of the pieces are rounded or sub-rounded. Eighteen sedimentary pieces contain holes or portions of holes due to the activities of boring animals such as pholads. An analysis of the asphalt failed to indicate if it is of natural origin or a refined product.

The varied lithology, the rounding of a large number of pieces, and the pholad-type borings indicate that the rocks have been transported from a shallow-water environment to the deep sea. Several transporting mechanisms are discussed. Rafting of the rocks by floating kelp is the most likely means of transport.

## INTRODUCTION

The 53 pebbles and small cobbles and the pieces of asphalt described in this paper were accidentally dredged from the floor of the deep sea by a trawl designed to obtain biological specimens in the midwater regions. The Scripps Institution of Oceanography research vessel *Paolina T* made a biological cruise in the Pacific Ocean southwest of Cedros Island, Baja California (fig. 1), in November-December 1951. R. L. Wisner attempted to trawl in the deep water near the sea floor but the trawl dragged bottom at a depth between 2000 and 2200 fathoms. Red clay was found in the trawl when it was brought back to the deck. Within the clay Wisner discovered the pieces of rock, the asphalt, and a few manganese dioxide nodules. He turned over the material to F. P. Shepard and R. S. Dietz, who gave it to the writer to investigate.

The material obtained with the trawl is an unusual deep sea bottom sample. The varied lithology of the pieces of rock, the rounding, and the pholad-type holes are indicative of a shallow water marine environment. Consideration of possible mechanisms which might have carried the pebbles and small cobbles to the deep water leads to the conclusion that kelp rafting is the most likely process. Kelp rafting has usually been considered a somewhat "academic" sedimentary process, but this material from the deep sea indicates that the process may be one of significance.

### *Location*

The trawling was done on the gently elevated sea floor on the southwest side of Cedros Deep, between Lat. 27° 11.4′ N, Long. 116° 30.6′ W and Lat. 27° 31.7′ N, Long. 115° 54.9′ W (fig. 1). The continental slope southwest of Cedros Island is steep, with a dip of 10 degrees between the 200 and 2400 fathom contours. On the seaward side of the trough the sea floor rises gently, and it is in this area that the trawl dragged bottom, at a depth between 2000 and 2200 fathoms.

### *Possible Number of Rocks Per Unit Area on Sea Floor*

The Isaacs-Kidd midwater trawl which obtained the sea floor sample is designed to obtain biological specimens in the midwater regions and is not intended for

[1] Navy Electronics Laboratory Professional Contribution no. 4. Contribution from the Scripps Institution of Oceanography, New Series No. 616.

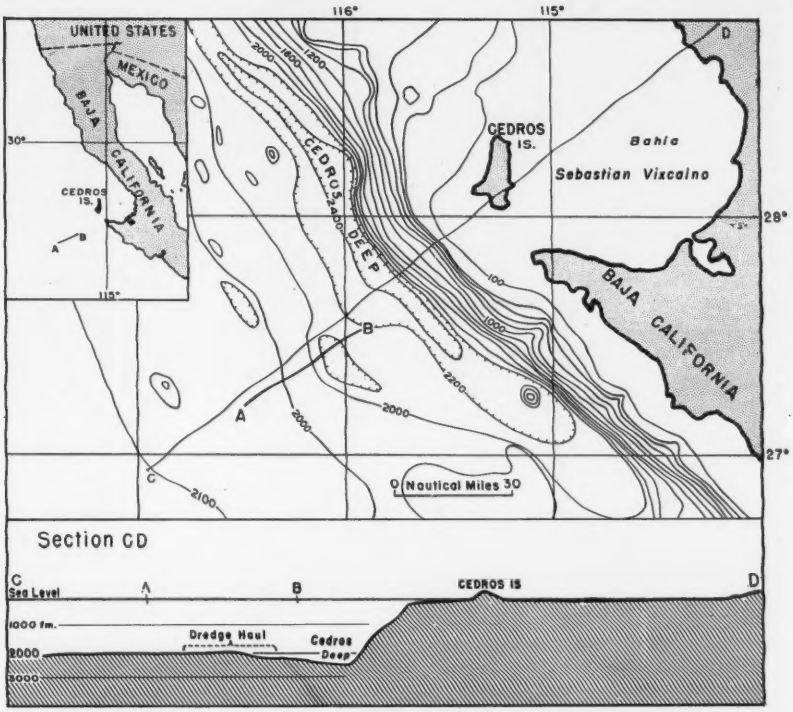


FIG. 1.—Location of trawling off Baja California where rocks and asphalt were obtained. Line AB represents distance covered by ship while trawl was in water. Section CD locates probable limits for the dredging.

use as a bottom dredge. It consists of a large tapering net with a rectangular opening 10 feet wide on the bottom edge. If it is assumed that the trawl effectively sieved a 10-foot swath of sediment for the entire distance it was towed at maximum depth, a calculation of the minimum number of rocks per unit area of the sea floor in the area dredged can be made. This assumption is thought to be unrealistic because it is likely that the trawl bounced and skipped along the bottom, probably only touching more elevated portions of the sea floor, digging into the sediment irregularly and sieving to some extent as it did so. Nevertheless, a calculation based on the maximum possible area dredged will give a minimum limit to the number of rocks per unit area, if the rocks are randomly distributed.

The ship moved approximately 37 nautical miles while the trawl was in the water (fig. 1), but a maximum of 3000 fathoms of cable was out for only about 15 nautical miles. Multiplying 15 nautical miles by the 10-foot width of the trawl gives an area of 0.033 square miles or 0.086 square km. Since 53 pieces of rock were obtained, the minimum density is 1600 rocks per square mile or 616 per square km. The actual density is thought to be much higher because it is very unlikely that the trawl sieved a

10-foot swath for 15 nautical miles of the sea floor.

ACKNOWLEDGMENTS

R. L. Wisner recognized the unusual nature of the pebbles he accidently obtained from the sea floor and his preservation of the material for study by marine geologists is appreciated. Rollin Eckis, Clifton W. Johnson and C. T. Brown of the Richfield Oil Corporation made possible the analysis of the asphalt and their help and interest are acknowledged. William R. Riedel kindly identified radiolaria from a limestone pebble. Garret L. Pribble aided in drafting.

Francis P. Shepard and M. N. Bramlette have critically read the manuscript. Robert S. Dietz and Henry W. Menard discussed the subject matter with the author, suggested changes in the manuscript, and read the final manuscript.

## DESCRIPTION OF SEDIMENT FROM THE TRAWL

### *General Statement*

Figure 2 is a photograph of all of the coarse material brought up by the trawl. The pebbles and small cobbles consist of an assortment of igneous, metamorphic, and sedimentary rocks. Pieces of a brittle asphalt and a few manganese dioxide nodules were obtained in addition to the rocks. The rounded pebbles can be noted in figure 2 and the pholad-type holes in figures 2 and 3. Thin sections of the igneous and metamorphic rocks have been examined, and an analysis of the asphalt has been made.

The three most significant features of the group of rocks are the varied lithology, the rounding of a number of pieces, and the animal borings. Each of these features is suggestive of the shallow-water environment near the coast, where rocks from various formations along the coast are mixed together and abraded.

### *Rock Types*

Of the fifty-three pebbles and small cobbles, 13 are igneous, 12 are metamorphic, and 28 are sedimentary. The igneous pieces include diorites, tonalites, and rhyolites, but basalt is not present.

FIG. 2.—Pebbles, asphalt and manganese dioxide nodules from the deep ocean off Baja California. Igneous, metamorphic and sedimentary rocks are present. Note pholad-type borings in some pebbles. At lower right, below scale, are pieces of asphalt.

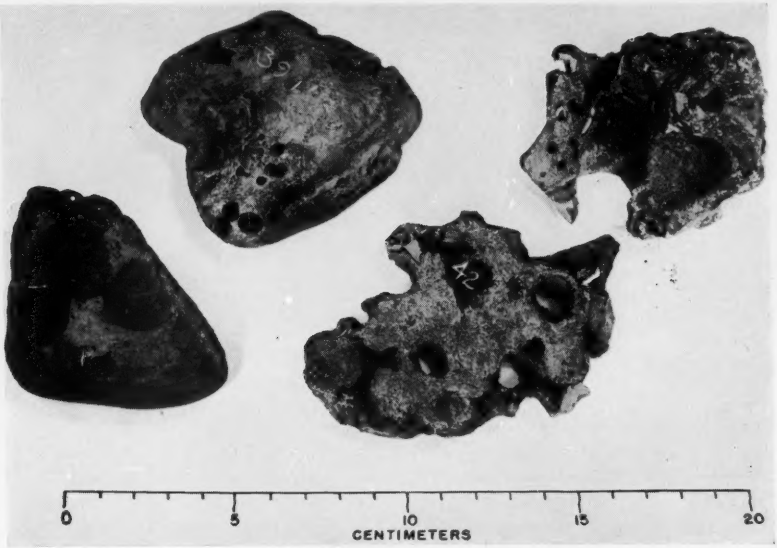


FIG. 3.—Sedimentary rocks with pholad-type borings. Note that one piece has been bored after being rounded.

Volcanoes of the Pacific petrographic province produce olivine basalt and petrographically related rocks; hence the absence of such rocks suggests a continental origin for the dredged-up rocks. Metamorphic pieces include a hornblende gneiss, quartzites, graywackes, and a silicified black shale. Sandstone and siltstone dominate in the sedimentary suite. Two pieces of tuff and one limestone piece are also present. William R. Riedel examined the calcareous rock and found that it contained Miocene radiolaria.

Table 1 lists the igneous and metamorphic rocks and gives an indication of the roundness of each fragment as a number based on visual comparison of the pieces with a chart devised by Krumbein (1941). Table 2 lists the sedimentary pieces with regard to rock classification and any important features which they may have, such as animal borings.

### *Animal Borings*

At least eighteen of the pebbles and small cobbles contain holes or portions of holes which have resulted from the activities of marine boring animals. Many of the holes closely resemble the type produced by the pholads—a circular cavity which increases in diameter with depth. The holes can be seen in a number of pebbles illustrated in figure 2. Figure 3 shows more closely the extent of borings in four of the larger pieces. Some of the rocks containing holes have been rounded prior to the development of the holes. No calcareous shells or hole linings were found in any of the cavities. Pholads and other boring animals usually choose shales, siltstones and sandstones in which to make their burrows, in preference to igneous and metamorphic rocks which are harder. All of the eighteen pieces which contain holes are relatively soft sedimentary rocks.

TABLE 1.—*Igneous and metamorphic rocks*

| Igneous rocks | Roundness |
|---|---|
| Diorite | .8 |
| Diorite | .7 |
| Diorite | .4 |
| Diorite | .2 |
| Diorite porphyry | .4 |
| Tonalite | .7 |
| Tonalite | .5 |
| Tonalite | .1 |
| Syenite porphyry | .8 |
| Calci-alkalic granite | .2 |
| Rhyolite | .8 |
| Rhyolite | .7 |
| Rhyolite | .2 |
| **Metamorphic rocks** | |
| Hornblende gneiss | .3 |
| Arkosic quartzite | .4 |
| Quartzite | .5 |
| Greywacke | .4 |
| Greywacke | |
| Greywacke | |
| Greywacke | |
| Silicified black shale | .5 |
| Quartz, unidentified rock | .6 |
| Unidentified | .2 |
| Unidentified | .2 |
| Unidentified | .1 |

Pholads are known to inhabit rocks in the lower intertidal zone and are abundant on the sea floor of the adjacent inner neritic zone. They are considered characteristic of shallow waters, although even generalized depth limits are not well known. Pholads are abundant in the rocky sides of Scripps Submarine Canyon off La Jolla, California to depths of 140 feet according to the writer's underwater observations. The rocky sea floor where kelp plants attach themselves contains a large population of pholads. *Pholadidea penita* has been dredged from a depth of 50 fathoms in San Francisco Bay (Hill and Kofoid, 1927).

Hanna (1952) discusses borings in rocks dredged from the continental slope off San Francisco, California. He found pholad-type borings in rocks from as deep as 600 fathoms but neither the animals nor remains of their shells were present. He considers pholads to be shallow water animals and, for lack of another explanation, attributes the deep occurrences of bored rocks to subsidence. On Station 51, at a depth between 180 and 80 fathoms, Hanna dredged up sandstone with numerous cavities containing the "nestling" mollusk, *Saxicava*.

The presence of animal borings, many which are the pholad type, in eighteen of the rocks brought up by the trawl, is a good indication that these rocks were transported from the near-shore marine environment to the deep water where they were found.

TABLE 2.—*Sedimentary rocks*

| |
|---|
| Sandstone, grains up to 0.5 mm. dia., arkosic |
| Sandstone, grains up to 0.5 mm. dia., arkosic |
| Sandstone, graded bedding medium fine grains to silt |
| Sandstone, fine grained, arkosic |
| Sandstone, fine grained |
| Sandstone, fine grained, arkosic, many animal borings |
| Sandstone, fine grained, animal borings, impregnated with $MnO_2$ |
| Sandstone, fine grained, micaceous, animal borings |
| Sandstone, fine grained, animal borings, $MnO_2$ coating 2–3 mm. |
| Sandstone, fine grained, animal borings, $MnO_2$ coating 2–3 mm. |
| Sandstone, fine grained, dark minerals, $MnO_2$ coating 2–4 mm. |
| Sandstone, very fine grained, micaceous, animal borings |
| Siltstone, biotite present, animal borings |
| Siltstone, animal borings |
| Siltstone, animal borings |
| Siltstone, biotite present, animal borings |
| Siltstone, specimen rounded, many animal borings |
| Siltstone, specimen rounded, large animal borings |
| Siltstone, animal borings |
| Siltstone, animal borings |
| Siltstone, animal borings |
| Siltstone, animal borings |
| Siltstone, micaceous, animal borings, $MnO_2$ coating 2–3 mm. |
| Siltstone, biotite present |
| Siltstone, $MnO_2$ coating 3–5 mm. |
| Limestone, contains Miocene radiolaria |
| Tuff, fine particle, size, animal borings |
| Tuff, very fine particle size |
| Manganese dioxide nodule without rock nucleus |
| Manganese dioxide nodule without rock nucleus |
| Manganese dioxide nodule without rock nucleus |

### *Manganese Dioxide Coatings*

All of the rocks brought up in the trawl were coated with manganese dioxide. The coating was only a fraction of a millimeter thick on the rounded pieces of igneous and metamorphic rock, but was 1 to 5 mm thick on some angular pieces of siltstone and sandstone. A few pieces of sandstone, when broken open, revealed spots of manganese dioxide throughout the rock. The oxide appeared to be growing within the porous material. Three manganese dioxide nodules were included in the trawl which did not contain visible rock fragments for nuclei.

### *Red Clay and Its Contents*

Red clay is the usual sediment in the area dredged, judging from the greater part of the sediment brought up in the trawl. This agrees with Revelle's map (1944) of bottom sediments of the Pacific Ocean. A small amount of detrital material and an appreciable amount of organic remains were present in the sample examined. The organic remains include worm tubes, diatoms, radiolaria, fragments of fish teeth, tiny pelecypod shells, pelagic and benthonic Foraminifera tests, bone fragments, and echinoid plates. The detrital material consisted of a very few mineral and rock grains.

### *Foraminifera*

The Foraminifera within the red clay were examined with the idea that a displaced benthonic fauna might be found. The presence of a displaced, relatively shallow-water, fauna would suggest that sediment had been carried down the continental slope, across the bottom of the Cedros Deep trough, and up the gentle rise on the seaward side of the trough by a turbidity current or mass movement of sediment. Typical and indicative shallow-water species were not found among the benthonic fauna and therefore the fauna appears to be indigenous.

### *Asphalt*

Pieces of brittle asphalt (fig. 2) were included in the trawled material. Rollin Eckis of the Richfield Oil Corporation had some of the the asphalt analyzed in Richfield's Watson Laboratory to determine if possible whether it was a natural asphalt or a refined petroleum product. C. T. Brown of Watson Laboratory reported the following data: Acid No. 5.7; Saponification No. 8.7; Sulfur 7.24%. An acid number less than one suggests a refined product and 2–15 a natural product but saponification numbers less than 15 suggest refined products. Thus the two points are contradictory. The brittle asphalt gave a clean, bright surface when broken and Brown felt that an underwater seepage of asphalt would be spongy and porous. His guess is that the asphalt probably did not occur naturally at the site where it was found.

Small quantities of a soft, black, tarry bituminous substance are frequently found in the sediments of California's continental borderland basins. Emery and Rittenberg (1952) discuss this material, which they noted in 85 out of 280 bottom samples they examined. They describe it as separate grains 0.2 to 2 mm in diameter or as a cement for detrital grains and Foraminifera tests. They found that its distribution showed no relation to depth of water or to kind of enclosing sediment (however, their studies were only of basin sediments, which usually occur at less than 1000 fathoms), and only a slight relation to oil producing areas on land. Some of the bituminous matter came from deep in cores, so the influence of men and ships can be discounted. It is known that early Indians of California made use of bitumen they collected along beaches for such purposes as lining bowls.

Perhaps the brittle asphalt dredged from the deep sea is in some way related in origin to the type of bituminous matter found in the basin sediments off southern California.

## MODE OF TRANSPORTATION

### *General Statement*

The nature of the pebbles indicates

that they probably were transported from a shallow water environment to the floor of the deep sea. The greater part of the sediment brought up by the trawl is red clay, containing a small amount of organic matter and a few detrital grains; this is the typical sediment for the area. The pebbles and small cobbles have resulted from a rather unusual sedimentary process which is independent of the processes which deposited the fine sediment in the area.

Agassiz (1902, p. 72) was puzzled by pebbles dredged up by the *Albatross* on its 1899–1900 cruise at a location approximately 570 nautical miles west of the position for the rocks described in this paper. Red clay, manganese dioxide nodules, flat slabs of palagonite tuff and some pebbles thinly coated with manganese dioxide were obtained from a depth of 2368 fathoms. The pebbles consisted of a portion of a rounded pebble of hornblende andesite, fragments of a well rounded pebble of black chert traversed by minute quartz veins, a subangular fragment of pale-green serpentine, and an angular fragment of fine-grained sandstone. The similarity between these pebbles and the ones described in this paper is close with regard to lithologic types represented and external form. No mention of animal borings is made by Agassiz. The two occurrences may or may not be due to a common sedimentary process.

### *Possible Methods of Emplacement of the Pebbles*

*Turbidity current or mass movement transport.*—Turbidity currents and mass movements under favorable conditions are believed to be capable of transporting sand and perhaps coarser materials down the continental slopes and out onto the deep sea floor. The continental slope is steep off Cedros Island, with a 10 degree dip, and should be capable of furthering the progress of any such processes which might originate on the slope. However, the location of the pebbles southwest of Cedros Deep, 300 to 400 fathoms above the lowest part of the trough, presents an obstacle to the mechanism. It might be considered that the pebbles were transported before the trough developed, but if this had happened they probably would be too deeply buried in sediment to be obtained with a dredge.

The large size of the pebbles relative to the fine sand that is usually carried out onto the deep sea floor and ascribed to turbidity currents is considerable, and would indicate a very capable transporting mechanism. If the pebbles had been transported by turbidity current action it would seem that smaller pebbles, coarse, medium, and fine sand and shallow water benthonic Foraminifera would have been deposited along with the coarse material. With the exception of a few coarse rock grains these finer fractions are not present and a displaced benthonic Foraminifera fauna is not evident. Thus, turbidity currents and mass movements are an unlikely cause for the rocks being in the deep sea.

*Subsidence of submarine bank.*—Tertiary and Quaternary movements of land off southern California have been of such significant magnitudes that the possibility of the subsidence of a submarine bank might be considered responsible for the pebbles. The continental borderland off southern California is considered to have broken up and subsided in the Miocene (Emery and Shepard, 1945) but the present submerged continental area is generally at less than 1000 fathoms and is elevated by about 1000 fathoms from the true deep sea floor. It is considered unlikely that a continental area off Baja California has sunk away to become a part of the deep sea floor, but if such an event has happened it might explain the presence of the pebbles.

Two banks, Fortymile Bank and Thirtymile Bank, lie off San Diego at distances implied by their names. The summits of these banks lie at 43 and 130 fathoms respectively. At a depth of 210 fathoms on Fortymile Bank rounded cobbles and a piece of rock containing pholad-type holes have been dredged.

The rounding and pholad-type holes are apparently not due to processes acting at the present time and may have resulted from sinking of the bank or from a lowered sea level during the Pleistocene. If such banks were to be submerged to 2100 fathoms and remain free of excessive sediment, then a dredge haul made near the summit of one might obtain an assemblage of fragments similar to those here described.

Two considerations tend to discredit the subsidence argument. A subsidence of land of the order of 2000 fathoms, to become a part of the deep sea floor, is inconsistent with the theory of permanency of the ocean basins. The second consideration is that no phosphorite was found among the group of rocks, yet this authigenic mineral is commonly present on topographic highs in the continental borderland region. If a submarine bank in the continental borderland region had become deeply submerged it probably would contain pieces of phosphorite together with abraded rock fragments, and a sample of more than 50 pieces should include some phosphorite.

*Ice rafting.*—Rafting of glacially rounded rock fragments by icebergs has left pebbles, cobbles and boulders widely disseminated on a portion of the floor of the North Pacific Ocean. According to Menard (personal communication), any dredge haul taken in the Gulf of Alaska almost invariably brings up ice-rafted material except in near-shore areas where deposition of terrigenous materials has been rapid enough to bury the Pleistocene sediments. The southern limit of glacial-marine sediments is approximately 48 degrees north latitude (Menard, in press) but a few icebergs probably were carried farther south by the ocean currents which transport water southward off the western coast of North America. If the pebbles from near Cedros Deep or from the *Albatross* sample are of ice-rafted origin then they represent the most southernly occurrence of glacial-marine sediment yet reported in the North Pacific Ocean.

Agassiz (1902, p. 72) considers that the fragments he described from the deep sea west of Baja California have all the characteristics of glacial-worn pebbles, and gives the following discussion concerning their origin in the deep sea:

"As the shark's teeth and cetacean bones found in the red clay seem to indicate that since the Tertiary times there have been very insignificant deposits at great distances from the continental areas, similarly we may be tempted to assume that these pebbles, which could not have been transported to their present locality by any agency of the present epoch, were carired to it during the glacial epoch, the thin coating of manganese dioxide indicating how small have been the bottom deposits since the glacial period."

The assumption of glacial origin for these pebbles is not unreasonable. The point concerning the thin coating of manganese dioxide as an indication of the small rate of accretion of the material since the glacial period is not necessarily valid, however. On Gilbert Seamount in the Gulf of Alaska, Menard (personal communication) found ice-rafted pebbles which had only a thin wash of manganese dioxide in more than 99 per cent of the cases, yet ice-rafted pebbles were also found several inches deep in pieces of manganese dioxide crust.

The presence of pholad-type holes in 18 out of the 53 pebbles from the sea floor off Cedros Island is notable because these features have not been found in any of a large number of ice-rafted pebbles, cobbles, and boulders from the Gulf of Alaska. according to Menard (personal communication). It would seem that the presence of a high percentage of pholad-type holes implies a non-ice-rafted origin for the pebbles described in this paper and the great distance from the Gulf of Alaska helps strengthen the argument.

*Kelp rafting.*—The ability of floating kelp to transport pebbles and small cobbles has been discussed by Emery and Tschudy (1941). Kelp is a form of marine algae which attaches itself to the

sea floor in waters from about 20 to 90 feet in depth by means of root-like holdfast structures. The plant extends upward to the surface where its photosynthetic tissue can function best. The plants grow to a size of a hundred or more feet in length, and *Macrocystis*, the largest of the marine algae, commonly is 200 feet long and occasionally longer. In a number of species, gas filled floats keep the long blade of the plant near the surface. The float cavity of *Pelagophycus*, a species common off southern and Baja California, is reported by these authors to be as large as 120 cubic inches. The buoyancy of entire plants is considerable. Kelp grows almost exclusively on rocky bottoms because of the necessity of a good anchorage to prevent being carried away by currents. It often grows in extensive beds at depth between 30 and 90 feet, and the sea floor below these kelp beds usually consists of bedrock and loose boulders, cobbles and pebbles. Pholads and other boring animals are extremely abundant in these rocky areas, according to the author's observations while diving with the aid of an Aqua-lung.

Kelp plants are often torn loose from the bottom and washed ashore during storms. Pebbles are commonly found attached to the holdfasts. Emery and Tschudy estimated that more than 100 pebbles with holdfasts attaches were washed ashore at La Jolla after one day of large waves in 1940. In one of their illustrations these authors show photographs of some of the pebbles with holdfasts attached. The pebbles are both angular and rounded, and one piece contains worm and pholad borings.

Kelp beds are present along the Pacific coast from Alaska to south of Mexico. The circulation of surface water off Baja California provides the needed mechanism to carry the floating kelp out to sea. Throughout a good part of the year the currents move the surface waters southward along the coast of Baja California and at times turn seaward in the vicinity of Cedros Island.

Pholads are also found from Alaska to Central America and even farther south. According to Ricketts and Calvin (1939, p. 105–106), *Pholadidea ovoidea* is found from the Bering Sea to the Gulf of California, *P. penita* from Alaska to Ecuador, and *Saxicava pholadis* from the Arctic to Panama. The widespread occurrence of pholads and kelp in the same environment suggests that kelp-rafted rocks should contain a significant proportion of pieces with borings in them.

Kelp is frequently found floating far from land. A considerable amount of kelp was noted at sea off Baja California in August 1952 by the author while participating in Expedition Shellback of the Scripps Institution of Oceanography. A mat of kelp about 15 by 15 feet in size was sighted 34 nautical miles from land (Lat. 24° 30′N, Long. 112° 50′W) off Cape San Lazaro. Isolated pieces were sighted occasionally as the ship moved from this position up to Cedros Island. About 55 nautical miles north of Cedros Island and 21.5 nautical miles from land numerous pieces of kelp were sighted from the ship. A quantitative estimate of the number of pieces per unit area was made by counting pieces apparently greater than three feet long which passed within about 150 feet of the ship during a 15 minute period as the ship moved along at 11.5 knots. Fifty-one pieces were counted, implying 240 pieces per square nautical mile over the distance covered.

Emery and Tschudy (1941) mention kelp being seen 250 miles from land off southern California. In 1951 during the joint Scripps Institution of Oceanography-U. S. Navy Electronics Laboratory expedition, Northern Holiday, numerous pieces of kelp were sighted at distances as great as 300 miles from land. A number of pieces were picked up and one of them had a rock attached measuring 8 by 5 by 4 cm. All of the pebbles described in this paper are of a size that floating kelp could easily transport. Boulders and large cobbles are easily rafted by ice but there is a limit to the buoyancy of kelp plants. The absence of boulders and large cobbles in the sample

favors kelp rafting. It is therefore reasonable that the pebbles described in this paper were transported by floating kelp, and of all the arguments considered, kelp rafting has the most points in its favor. The pebbles described by Agassiz (1909) may also be due to kelp rafting, but they were found about 600 nautical miles from land rather than 60 nautical miles.

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FIGS. 1–11, MARCH, 1953

# CORRELATION OF THE TILLS OF NORTHEASTERN OHIO BY SIZE ANALYSIS

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## ABSTRACT

Mechanical analyses of till samples from northeastern Ohio are used to correlate multiple tills of Tazewell, early Cary, and late Cary ages. Drift of Tazewell and early Cary ages shows a remarkable textural homogeneity and late Cary drift, although rather variable over the whole area, is homogeneous within each of its lobes of advance.

On the basis of the mechanical analyses it is proposed that multiple tills in general become successively finer grained upward in the section. It is suggested that material in tills is not as local in origin as has been previously believed.

## INTRODUCTION

In his field study of the Wisconsin and earlier drifts in northeastern Ohio, Dr. G. W. White collected a series of samples of unleached Wisconsin till of Tazewell, early Cary, and late Cary ages. It is proposed to determine how the size distribution, carbonate content, heavy minerals, and clay mineralogy of the tills vary in order to determine which physical characteristics may be useful in correlation of the individual drift sheets. The purpose of this report is to present the results of a study of the size distribution of the samples.

The author wishes to express his gratitude to Dr. White for the opportunity to study these samples and for information on the glacial geology of the samples, and to Dr. J. L. Hough for his assistance and advice in technical sedimentation procedures, and collection and treatment of data.

The localities at which the samples were collected are shown in figure 1. Each locality is shown as a circle which is divided into quadrants. The black quadrants indicate the age of the sample or samples collected at that locality, the NW quadrant indicating a late Cary sample, the NE quadrant an early Cary sample and the SW and SE quadrants a Tazewell sample. Most of the samples were collected from cut banks of streams, from road cuts, or from recent excavations and in all cases are calcareous. Approximately ⅔ of the samples are unleached, but oxidized, till from horizon 4 (White, 1951, p. 972; Leighton and MacClintock, 1930), since in these places the unoxidized zone, horizon 5, is absent or not exposed. A 1500 to 2500 gram "channel-type" sample was collected with a mattock from a cleared portion of the exposed face and the material was preserved in a canvas sack.

## ANALYTICAL PROCEDURE

Each sample was air dried and then disaggregated by gentle crushing with a steel pestle. The sample was placed for crushing on brown kraft paper in the bottom of a wooden drawer rather than on a completely rigid surface. As pebbles larger than 10 mm were picked from the sample during the crushing, the material analyzed was less than 10 mm in diameter and essentially only the matrix of the till was analyzed. A representative sample was obtained by repeatedly passing the material through a Jones sample splitter until only a 30 to 40 gram sample remained. This was weighed and the coarse and fine fractions were roughly split by wet sieving through an .088 mm sieve. The coarse fraction was then shaken

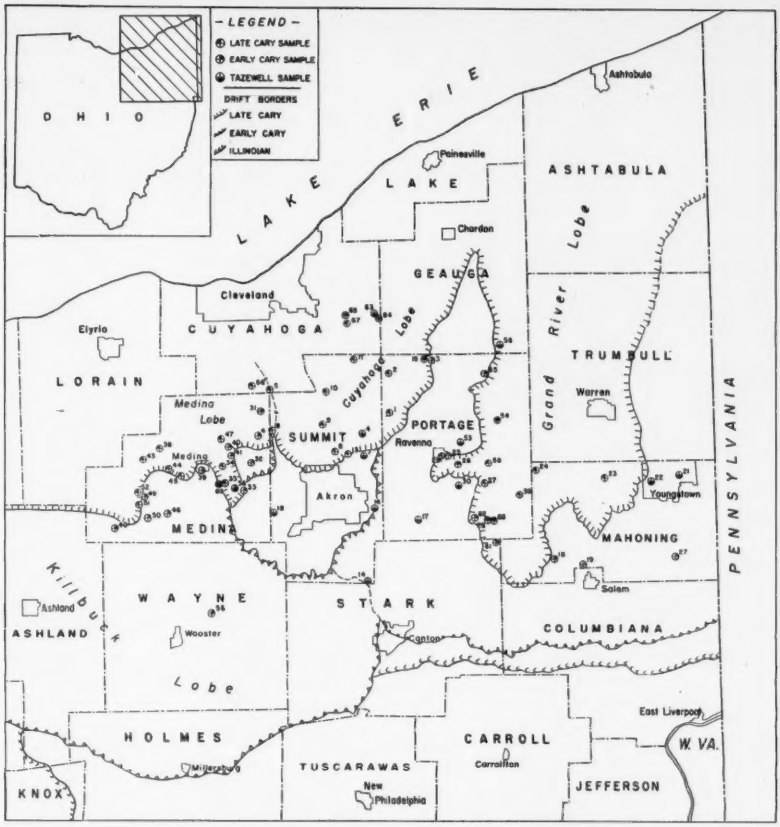


FIG. 1.—Till sheet boundaries and sample localities of northeastern Ohio (boundaries mapped and samples collected by G. W. White).

through a set of Tyler sieves for ten minutes on a Ro-Tap machine and the individual fractions thus obtained were weighed. The fine material caught in the pan was added to the fine fraction obtained in the wet sieving and this fraction was analyzed by the pipette method of Krumbein and Pettijohn (1938, pp. 166–172). Sodium oxalate in a concentration of .01 N was found to be the most suitable dispersing agent. The results of the analyses are shown in table 1.

After having analyzed 54 samples completely it was decided that it would be satisfactory to determine only the percentages of sand, silt, and clay for the remaining samples, since it appeared that the plotting of these percentages on a triangular diagram was sufficiently distinctive to show the correlation desired and that the further data obtained from complete analyses were not sufficiently useful to warrant the time needed to run the analyses and plot the cumulative

TABLE 1.—*Mechanical analyses*

| Sample no. | Per cent by weight in each grade size. Grade sizes in millimeters | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 10.00–4.00 | 4.00–2.00 | 2.00–1.00 | 1.00–.500 | .500–.250 | .250–.125 | .125–.088 | .088–.0442 | .0442–.0312 | .0312–.0156 | .0156–.0078 | .0078–.0039 | .0039–.00195 | .00195–.00098 | .00098–.00049 | .00049– |
| 1 | | | | | | | 2.97* | 5.52 | 2.23 | 12.61 | 16.43 | 17.23 | 11.93 | 12.80 | 18.27† | |
| 2 | 0.00 | 1.27 | 2.73 | 2.43 | 3.18 | 4.06 | 2.07 | 6.05 | 3.65 | 9.37 | 10.08 | 12.43 | 10.93 | 9.20 | 22.55† | |
| 3 | 8.52 | 3.91 | 3.14 | 3.03 | 5.66 | 6.70 | 2.83 | 7.38 | 3.48 | 16.32 | 17.82 | 9.00 | 7.23 | 6.40 | 4.57† | |
| 4 | 2.00 | 3.70 | 5.50 | 5.29 | 7.34 | 8.94 | 4.34 | 11.35 | 10.15 | 10.33 | 9.55 | 6.70 | 3.05 | 3.32 | 3.08 | 5.33 |
| 5 | 0.00 | 3.23 | 3.38 | 3.33 | 4.14 | 4.62 | 2.33 | 8.90 | 2.15 | 10.97 | 14.95 | 6.85 | 12.12 | 11.25 | 11.70† | |
| 6 | | | | | | | 8.64* | 7.68 | 4.32 | 6.97 | 17.78 | 12.80 | 8.00 | 10.37 | 5.68 | 19.43 |
| 7 | 5.75 | 3.00 | 2.91 | 3.35 | 12.03 | 20.09 | 5.50 | 9.25 | 0.67 | 13.30 | 7.32 | 5.69 | 4.56 | 0.62 | 2.27 | 3.70 |
| 8 | 0.40 | 1.83 | 2.36 | 2.37 | 3.44 | 4.44 | 2.35 | 7.38 | 4.52 | 9.05 | 14.02 | 14.13 | 6.87 | 8.55 | 4.83 | 13.45 |
| 9 | | | | | | | 3.42* | 6.57 | 5.67 | 14.57 | 19.63 | 13.22 | 7.37 | 6.17 | 4.35 | 11.03 |
| 10 | | | | | | | 2.54* | 3.10 | 6.77 | 15.52 | 19.73 | 12.25 | 7.32 | 7.43 | 5.25 | 14.12 |
| 11 | | | | | | | 1.88* | 8.07 | 4.22 | 16.62 | 17.88 | 14.62 | 7.65 | 6.20 | 5.25 | 13.22 |
| 12 | 4.44 | 5.99 | 4.78 | 5.17 | 12.30 | 12.01 | 4.32 | 11.01 | 5.55 | 9.80 | 8.20 | 1.87 | 3.58 | 3.32 | 7.42† | |
| 13 | | | | | | | 3.61* | 5.35 | 4.37 | 14.66 | 16.93 | 15.13 | 9.37 | 7.02 | 15.17† | |
| 14 | 1.15 | 4.30 | 4.96 | 5.05 | 11.19 | 11.59 | 4.09 | 10.72 | 3.98 | 11.08 | 8.37 | 6.71 | 4.17 | 3.88 | 8.90† | |
| 15A | 0.00 | 2.37 | 2.37 | 1.62 | 2.94 | 3.91 | 3.91 | 1.70 | 4.65 | 3.98 | 13.88 | 12.15 | 12.20 | 6.63 | 8.63 | 13.08 |
| 15B | 0.98 | 1.89 | 2.60 | 2.68 | 6.33 | 8.48 | 3.08 | 8.67 | 4.97 | 10.53 | 17.17 | 7.98 | 6.67 | 4.80 | 4.88 | 8.41 |
| 16 | 8.90 | 6.23 | 4.09 | 3.95 | 12.82 | 14.01 | 4.19 | 10.45 | 4.15 | 6.93 | 6.58 | 4.35 | 3.30 | 1.17 | 9.20† | |
| 17 | 3.58 | 4.47 | 5.24 | 6.50 | 16.33 | 13.67 | 4.41 | 8.20 | 4.27 | 8.15 | 6.30 | 4.60 | 3.78 | 3.55 | 7.01† | |
| 18 | 3.03 | 4.15 | 3.35 | 3.44 | 5.77 | 6.83 | 3.19 | 12.17 | 6.08 | 13.27 | 10.55 | 8.87 | 5.63 | 5.12 | 3.38 | 5.57 |
| 19 | 0.91 | 2.04 | 2.70 | 2.74 | 4.77 | 6.17 | 2.90 | 9.77 | 3.93 | 12.83 | 11.67 | 10.45 | 7.70 | 5.10 | 7.18 | 9.13 |
| 20 | 1.01 | 1.47 | 1.72 | 1.72 | 3.26 | 3.89 | 2.30 | 12.86 | 6.33 | 15.04 | 12.28 | 10.17 | 7.38 | 5.13 | 4.82 | 10.47 |
| 21 | 4.04 | 4.03 | 3.96 | 4.01 | 9.24 | 10.52 | 4.03 | 14.55 | 4.25 | 9.87 | 8.27 | 5.95 | 4.73 | 3.52 | 5.20 | 3.78 |
| 22 | 3.92 | 5.08 | 4.53 | 4.36 | 7.60 | 9.04 | 3.77 | 16.02 | 7.32 | 13.48 | 8.41 | 5.58 | 3.35 | 1.77 | 2.67 | 2.77 |
| 23 | | | | | | | 2.38* | 3.37 | 0.78 | 5.17 | 14.43 | 17.87 | 14.38 | 9.27 | 8.35 | 24.00 |
| 24 | | | | | | | 3.67* | 4.45 | 0.72 | 6.47 | 9.55 | 12.07 | 13.97 | 10.12 | 12.28 | 26.70 |
| 25 | 3.33 | 3.33 | 2.34 | 3.06 | 8.33 | 8.71 | 4.13 | 7.48 | 3.40 | 8.58 | 12.18 | 11.15 | 6.93 | 5.02 | 1.92 | 10.08 |
| 26A | 0.00 | 1.96 | 2.42 | 2.70 | 5.70 | 6.50 | 2.82 | 10.61 | 4.60 | 8.80 | 13.80 | 12.58 | 9.60 | 4.40 | 11.60 | 2.00 |
| 26B | | | | | | | 4.88* | 7.20 | 3.40 | 8.80 | 9.20 | 34.20 | 4.48 | 15.60 | 2.00 | 9.40 |
| 28A | 4.32 | 2.66 | 3.16 | 3.18 | 6.36 | 8.20 | 3.04 | 8.90 | 3.30 | 8.90 | 12.80 | 11.70 | 1.00 | 9.90 | 8.70 | 4.00 |
| 28B | 0.98 | 2.20 | 1.76 | 1.58 | 3.30 | 4.18 | 1.90 | 5.60 | 3.40 | 6.70 | 13.20 | 10.90 | 11.50 | 7.20 | 14.40 | 10.60 |
| 29 | | | | | | | 5.43* | 6.25 | 2.95 | 13.20 | 14.87 | 12.20 | 9.97 | 10.10 | 10.18 | 14.52 |
| 30 | 0.75 | 3.92 | 4.16 | 4.24 | 11.39 | 11.85 | 4.22 | 11.83 | 6.02 | 7.81 | 7.83 | 6.37 | 4.65 | 4.84 | 4.25 | 5.70 |
| 32 | 2.13 | 4.18 | 3.42 | 3.12 | 4.30 | 6.13 | 3.36 | 9.17 | 3.83 | 10.45 | 11.60 | 8.18 | 8.48 | 5.03 | 3.65 | 11.97 |
| 34 | | | | | | | 15.36* | 7.68 | 3.85 | 8.92 | 10.72 | 14.02 | 10.77 | 8.07 | 6.03 | 14.47 |
| 35 | | | | | | | 7.45* | 2.02 | 5.10 | 15.77 | 7.62 | 13.80 | 11.35 | 8.48 | 3.93 | 23.82 |
| 36A | 2.73 | 2.40 | 3.41 | 3.22 | 3.83 | 4.89 | 3.29 | 9.20 | 3.65 | 13.58 | 13.52 | 7.98 | 7.67 | 5.63 | 4.33 | 10.65 |
| 36B | 2.77 | 4.65 | 4.04 | 3.40 | 6.37 | 9.83 | 9.05 | 16.85 | 4.30 | 9.22 | 7.15 | 5.67 | 16.70‡ | | | |
| 38 | 0.97 | 2.26 | 3.58 | 3.33 | 4.20 | 5.05 | 3.18 | 6.20 | 3.45 | 10.08 | 12.23 | 9.45 | 9.57 | 8.12 | 5.40 | 12.90 |
| 39 | 0.53 | 2.96 | 3.00 | 3.34 | 4.69 | 6.18 | 4.46 | 9.33 | 4.92 | 10.43 | 11.97 | 9.18 | 8.15 | 5.62 | 4.27 | 11.13 |
| 42 | 2.71 | 4.10 | 3.98 | 3.78 | 5.23 | 5.56 | 3.09 | 7.35 | 4.23 | 13.08 | 13.23 | 9.28 | 7.40 | 6.52 | 1.73 | 8.72 |
| 43 | 0.37 | 2.73 | 3.41 | 3.03 | 3.24 | 3.92 | 2.60 | 8.32 | 5.03 | 7.87 | 12.65 | 10.03 | 10.37 | 9.08 | 3.17 | 14.20 |
| 44 | 0.00 | 3.33 | 2.83 | 2.73 | 3.59 | 4.97 | 3.33 | 7.98 | 4.42 | 8.33 | 11.42 | 9.50 | 10.00 | 7.97 | 5.25 | 14.38 |
| 49 | 3.64 | 4.22 | 3.37 | 2.85 | 3.13 | 4.64 | 2.84 | 8.52 | 4.45 | 10.48 | 12.80 | 9.10 | 8.12 | 5.55 | 3.63 | 12.65 |
| 50 | 5.74 | 4.97 | 3.60 | 3.66 | 4.46 | 5.01 | 2.97 | 7.83 | 3.80 | 10.33 | 11.63 | 7.85 | 8.12 | 5.15 | 2.98 | 11.90 |
| 52 | 3.37 | 4.64 | 3.54 | 3.40 | 4.26 | 4.80 | 3.00 | 8.53 | 3.42 | 8.60 | 10.82 | 7.60 | 9.57 | 7.10 | 4.63 | 12.72 |
| 54A | 1.68 | 4.34 | 4.60 | 4.52 | 7.30 | 7.82 | 3.42 | 8.40 | 4.30 | 14.40 | 14.40 | 8.20 | 2.40 | 7.00 | 6.00 | 1.00 |
| 54B | 0.28 | 1.41 | 1.95 | 2.12 | 4.26 | 4.63 | 1.65 | 5.40 | 1.30 | 9.80 | 2.90 | 12.70 | 12.40 | 10.80 | 14.50 | 12.00 |
| 55 | 2.40 | 3.80 | 4.90 | 5.60 | 9.10 | 7.30 | 2.60 | 9.83 | 13.33 | 2.00 | 12.33 | 6.50 | 13.83 | 5.83 | 0.50 | 0.83 |
| 56 | 3.58 | 4.76 | 4.24 | 4.08 | 8.32 | 9.56 | 4.02 | 10.00 | 6.33 | 16.65 | 6.00 | 6.57 | 2.16 | 8.85 | 4.16 | 0.66 |
| 58 | | | | | | | 7.39* | 9.00 | 2.33 | 5.50 | 12.18 | 13.33 | 19.50 | 17.15 | 3.67 | 10.63 |
| 59 | | | | | | | 1.34* | 4.09 | 1.61 | 4.12 | 8.03 | 18.68 | 7.84 | 9.80 | 11.86 | 33.17 |
| 60 | | | | | | | 7.71* | 5.82 | 3.08 | 9.37 | 11.55 | 12.13 | 11.00 | 10.35 | 9.88 | 19.45 |
| 61 | 0.30 | 1.40 | 2.70 | 2.68 | 5.46 | 9.26 | 3.80 | 8.07 | 5.11 | 10.65 | 9.93 | 9.05 | 6.52 | 6.33 | 8.04 | 10.50 |
| 62 | 3.98 | 1.87 | 1.87 | 1.61 | 4.01 | 5.91 | 3.20 | 7.50 | 11.35 | 10.00 | 10.17 | 10.65 | 17.15 | 5.33 | 1.66 | 3.67 |

* Weight coarser than .088 mm.
† Weight finer than .00098 mm.
‡ Weight finer than .0039 mm.

TABLE 2.—*Percentage composition and statistical values for 76 till samples*

| Sample No. | Age[1] | Percentages | | | Mean (M) | Sorting Factor ($S_0$) | $Q_1$ | $Q_3$ |
|---|---|---|---|---|---|---|---|---|
| | | Sand | Silt | Clay | | | | |
| 1-130 | LC | 5.5 | 51.5 | 43.0 | .0052 | 3.16 | .0015 | .015 |
| 2-144 | LC | 20.0 | 37.0 | 42.0 | .0060 | 5.23 | .0012 | .033 |
| 3-152 | EC | 37.0 | 45.0 | 18.0 | .0240 | 5.48 | .0066 | .220 |
| 4-181 | T | 42.0 | 43.0 | 15.0 | .0420 | 4.89 | .0100 | .033 |
| 5-191 | LC | 26.0 | 39.0 | 35.0 | .0130 | 5.63 | .0022 | .070 |
| 6-192 | LC | 12.0 | 46.0 | 42.0 | .0064 | 4.07 | .0012 | .020 |
| 7-197 | T | 58.0 | 31.0 | 11.0 | .105 | 4.04 | .0160 | .270 |
| 8-200 | LC | 21.0 | 45.0 | 34.0 | .0105 | 5.05 | .0017 | .043 |
| 9-201 | LC | 14.0 | 57.0 | 29.0 | .0090 | 3.75 | .0028 | .028 |
| 10-206 | LC | 10.0 | 56.0 | 34.0 | .0090 | 3.16 | .0016 | .022 |
| 11-212 | LC | 10.0 | 58.0 | 32.0 | .0086 | 3.31 | .0020 | .022 |
| 12-218 | T | 55.0 | 30.0 | 15.0 | .085 | 4.66 | .0165 | .360 |
| 13-223 | LC | 14.0 | 54.0 | 32.0 | .0090 | 3.21 | .0025 | .026 |
| 14-225 | T | 48.0 | 35.0 | 17.0 | .055 | 5.51 | .0088 | .270 |
| 15A-230A | LC | 17.0 | 42.0 | 41.0 | .0068 | 4.24 | .0015 | .027 |
| 15B-230B | EC | 30.0 | 45.0 | 25.0 | .0155 | 5.00 | .0040 | .100 |
| 16-234 | T | 60.0 | 27.0 | 13.0 | .125 | 5.12 | .0170 | .450 |
| 17-237 | T | 58.0 | 28.0 | 14.0 | .125 | 4.84 | .0155 | .365 |
| 18-240 | EC | 36.0 | 45.0 | 19.0 | .0280 | 4.91 | .0062 | .150 |
| 19-242 | EC | 27.0 | 44.0 | 29.0 | .0145 | 5.12 | .0028 | .074 |
| 20-247 | EC | 21.0 | 54.0 | 25.0 | .0145 | 4.15 | .0031 | .052 |
| 21-253 | T | 48.0 | 35.0 | 17.0 | .0550 | 5.24 | .0094 | .260 |
| 22-206 | T | 47.0 | 42.0 | 11.0 | .0540 | 4.08 | .0155 | .260 |
| 23-262 | LC | 4.0 | 40.0 | 56.0 | .0030 | 3.88 | .00054 | .0062 |
| 24-263 | LC | 6.0 | 31.0 | 63.0 | .0021 | 4.19 | .00044 | .0078 |
| 25-304 | EC | 37.0 | 39.0 | 24.0 | .0190 | 6.02 | .0042 | .175 |
| 26A-306A | EC | 27.0 | 39.0 | 27.0 | .0125 | 4.66 | .0033 | .072 |
| 26B-306B | LC | 9.0 | 45.5 | 32.5 | .0053 | 3.01 | .0017 | .0155 |
| 27-309 | LC | 18.0 | 58.5 | 45.0 | | | | |
| 28A-310A | EC | 35.5 | 37.0 | 23.5 | .0180 | 6.02 | .0044 | .160 |
| 28B-310B | LC | 18.5 | 47.0 | 44.5 | .0056 | 5.68 | .00096 | .031 |
| 29-311 | LC | 8.0 | 47.0 | 45.0 | .0052 | 4.22 | .00098 | .0175 |
| 30-313 | T | 45.0 | 35.0 | 20.0 | .0485 | 5.87 | .0070 | .240 |
| 31-314 | EC | 27.0 | 45.0 | 28.0 | | | | |
| 32-316 | EC | 31.0 | 39.0 | 30.0 | .0155 | 6.35 | .0026 | .105 |
| 33-317 | EC | 26.5 | 51.0 | 22.5 | | | | |
| 34-322 | LC | 19.0 | 42.0 | 29.0 | .0066 | 5.03 | .00145 | .037 |
| 35-323 | LC | 9.0 | 43.0 | 48.0 | .0043 | 6.21 | .00054 | .021 |
| 36A-325A | EC | 28.0 | 44.0 | 28.0 | .0155 | 5.10 | .0030 | .081 |
| 36B-325B | T | 51.0 | 32.0 | 17.0 | .0640 | 4.34 | .0098 | .185 |
| 37-326 | EC | 32.0 | 41.0 | 27.0 | | | | |
| 38-332 | LC | 25.0 | 39.0 | 36.0 | .0105 | 6.21 | .0017 | .066 |
| 39-333 | EC | 30.0 | 41.0 | 29.0 | .0150 | 5.70 | .0027 | .088 |
| 40-336 | EC | 18.5 | 54.5 | 27.0 | | | | |
| 41-337 | EC | 31.0 | 46.5 | 22.5 | | | | |
| 42-340 | EC | 32.0 | 43.0 | 25.0 | .0180 | 5.62 | .0041 | .130 |
| 43-349 | LC | 22.0 | 31.0 | 37.0 | .0094 | 5.18 | .00185 | .050 |
| 44-350 | LC | 24.0 | 38.0 | 38.0 | .0092 | 6.02 | .00165 | .060 |
| 45-351 | LC | 21.0 | 45.0 | 34.0 | | | | |
| 46-355 | EC | 26.0 | 47.0 | 26.5 | | | | |
| 47-358 | LC | 24.0 | 42.0 | 34.0 | | | | |
| 48-362 | EC | 28.0 | 49.0 | 27.0 | | | | |
| 49-364 | EC | 28.0 | 42.0 | 28.0 | .0145 | 5.74 | .0026 | .086 |
| 50-365 | EC | 34.0 | 49.0 | 28.0 | .0175 | 7.51 | .0030 | .170 |
| 51-366 | LC | 22.0 | 45.0 | 33.0 | | | | |
| 52-371 | LC | 31.0 | 35.0 | 34.0 | .0130 | 7.40 | .0020 | |

[1] Age notations: T = Tazewell, EC = early Cary, LC = late Cary.

TABLE 2.—(*Continued*)

| Sample No. | Age[1] | Percentages | | | Mean (M) | Sorting Factor ($S_0$) | $Q_1$ | $Q_3$ |
|---|---|---|---|---|---|---|---|---|
| | | Sand | Silt | Clay | | | | |
| 53-378 | T | 51.0 | 33.0 | 16.0 | | | | |
| 54A-381A | EC | 39.0 | 45.0 | 16.0 | .0150 | 4.99 | .0080 | |
| 54B-381B | LC | 19.0 | 29.0 | 51.5 | .0036 | 5.44 | .00084 | |
| 55-384 | EC | 39.0 | 40.0 | 21.0 | .0390 | 6.28 | .0066 | |
| 56-386 | T | 43.0 | 41.0 | 16.0 | .0400 | 4.96 | .0105 | |
| 57-394 | EC | 33.5 | 42.5 | 24.0 | | | | |
| 58-401 | LC | 12.0 | 38.0 | 50.0 | .0038 | 3.06 | .0016 | |
| 59-405 | LC | 4.0 | 34.0 | 62.0 | .0014 | 4.48 | .00031 | |
| 60-406 | LC | 10.0 | 39.0 | 51.0 | .0038 | 4.77 | .00070 | |
| 61-408 | EC | 29.0 | 39.0 | 22.0 | .0150 | 6.78 | .0020 | |
| 62-410 | EC | 26.0 | 46.0 | 28.0 | .0170 | 5.39 | .0035 | |
| 63-506 | T | 46.0 | 30.0 | 24.0 | | | | |
| 64-509 | EC | 19.0 | 39.0 | 42.0 | | | | |
| 65-513 | EC | 35.0 | 41.0 | 23.5 | | | | |
| 66-522 | LC | 23.0 | 40.0 | 36.5 | | | | |
| 67-537 | LC | 23.5 | 41.5 | 35.0 | | | | |
| 68A-545A | EC | 36.0 | 38.0 | 26.0 | | | | |
| 68B-545B | LC | 13.0 | 37.0 | 50.0 | | | | |
| 69A-570A | T | 46.0 | 36.5 | 17.5 | | | | |
| 69B-570B | EC | 31.5 | 47.0 | 21.5 | | | | |
| 69C-570C | LC | 10.0 | 22.0 | 77.0 | | | | |

curves. These samples were treated in the same manner as the samples on which the complete analyses were run up to the wet sieving stage. Instead of wet sieving these samples through an .088 mm sieve, an .062 mm sieve was used. The coarse fraction was dry sieved through an .062 mm sieve to remove any fines which were not removed during the wet sieving and the dried coarse fraction was weighed. The fine fraction was then placed in a sedimentation cylinder and dispersed following the same procedure used for the complete analyses. One pipette sample was taken to determine the percentage of material finer than .0039 mm in the sample. This was designated as the clay fraction, the material between .0039 mm and .062 mm the silt fraction and the material larger than .062 mm the sand fraction, following Wentworth's grade scale (1922, pp. 377–392), with the exception that material up to 10 mm was included as sand for the sake of convenience. The percentages obtained in this manner, as well as the percentages calculated from the data obtained for the samples analyzed completely, are tabulated in table 2.

## STATISTICAL TREATMENT OF THE DATA

The results of the mechanical analyses are shown in tables 1 and 2. Each sample has been given a number such as 1–100, the 1 representing a digit in a consecutive numbering system and used throughout the text to refer to the samples and the 100 being the number assigned to the samples in the field and here presented for later comparisons of other studies on the samples.

In order to visualize more easily the percentage values in table 2, they have been plotted as points on a triangular diagram (fig. 2) with the corners of the triangle equal to 100 per cent sand, silt, and clay. The median sizes (M) and the sorting factors ($S_0$) of the samples have also been tabulated in table 2. The mean size of the sample represents the grain size at 50 per cent of the total range of the sample (Krumbein and Pettijohn, 1938, p. 229) and the sorting factor is computed by using the formula $(Q_1/Q_3)^{1/2}$ as developed by Trask (1932, pp. 60–67). The quartiles ($Q_1$ and $Q_3$) from which the sorting factors were computed are also given

in Table 2 and represent the grain sizes at 25 per cent ($Q_3$) and 75 per cent ($Q_1$) of the total range (Krumbein and Pettijohn, 1938, pp. 223–225).

For purposes of correlation the percentage composition has the most value. Mean size is of some value, but less so than the percentage composition, since there is some overlap of these values between the late Cary and early Cary tills.

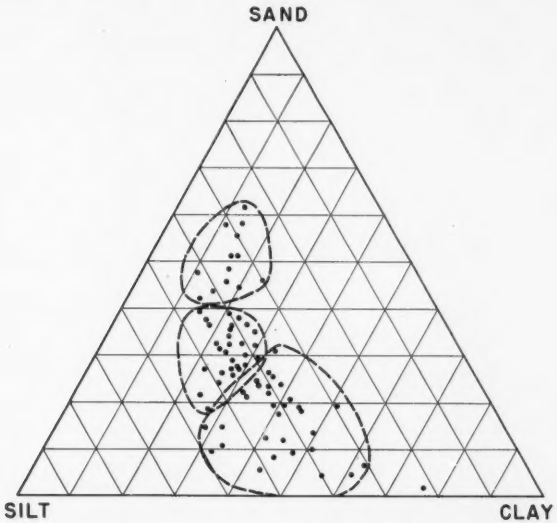


FIG. 2.—Composition of 76 till samples from three tills in northeastern Ohio.

The sorting factors, though of no value as a tool of correlation, are nevertheless of some academic interest, as will be shown later. Since no correlation or significance was found in the skewness or the quartile deviations of the samples these have not been tabulated.

### CORRELATION OF THE MULTIPLE DRIFTS

The investigations of White (1950, p. 1574; 1951a, p. 976, 1951b; 1953) show that the various Wisconsin drifts reach the limits shown in figure 1. The Tazewell, or early Wisconsin drift, is exposed at the surface over about 250 square miles in Summit and adjacent counties, as shown in figure 1. It is also found at certain localities cropping out beneath later drift. The early Cary drift is exposed over many hundred square miles and is also found at many places cropping out beneath late Cary drift.

Determinations of the age of the tills depends on a combination of stage of topographic development, depth of leaching, texture of the till, and soil types (White and Shepps, 1952). In the field it was found that sufficient differences in texture existed to make age determinations on this evidence alone. This was particularly true in differentiating Tazewell till from Cary till. In the present study samples of unquestioned age were first analyzed to establish reference criteria. Samples of questionable age were then analyzed and the data fitted into the existing charts. It was remarkable to observe the neatness of fit of unknown samples into the whole pattern.

W. C. Krumbein (1933, p. 404) noted the possibility of correlating tills on the basis of their variations in mechanical composition. By comparing the analyses

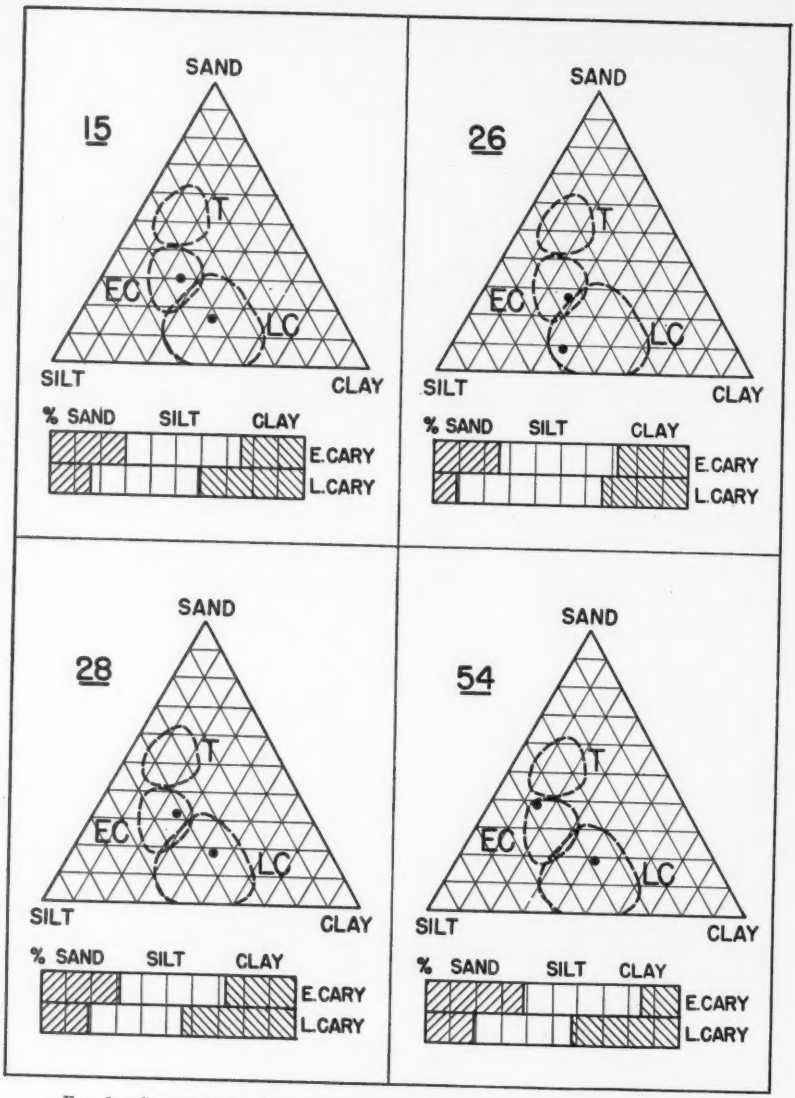


FIG. 3.—Comparison diagrams of multiple till samples collected from the same exposure (nos. 15, 26, 28, and 54).

of 76 samples as plotted in figure 2 it is apparent that Krumbein's assumption is correct, at least for the area considered in this report. The diagram also demonstrates the reasons for difficulty or facility in attempting to use field judgment of texture as a criterion for identifying the multiple tills of northeastern Ohio.

On the diagram (fig. 2) three groups of samples have been encircled, the uppermost (highest sand content) group containing samples which are Tazewell in age, the next lower group samples of early Cary age, and the lowermost (highest clay content) group samples of late Cary age. In no case does one group contain samples which belong to another and hence there is no overlap in the mechanical compositions as expressed in percentages of sand, silt, and clay. Though with the 76 samples analyzed there is no overlap between the early and the late Cary tills, their boundaries have been overlapped for it seems, because of the large area of contact of the group boundaries on the triangular diagram and the considerable variation in the mechanical composition of the late Cary till, not unlikely that the boundaries might overlap if more samples were run. It is interesting to note, however, that the present boundaries of the three groups were drawn after only 40 samples had been analyzed and the addition of 36 samples to the diagram did not alter the group boundaries where they are in contact.

At 7 localities more than one Wisconsin till is present in the same exposure. In these places the relative age of the tills present can be established with certainty by their position in the section. In figures 3 and 4 these samples have been plotted on individual triangular diagrams and on bar graphs. A combination of these samples, particularly in the case where all three tills are present, plus many other samples where the age was determined with certainty by field evidence, definitely establishes the ages of the encircled groups in figure 2.

One assumption which Krumbein (1933, p. 397) notes as prerequisite in any such study as this is that "The variations in the mechanical composition of the samples in any set of till samples should be so small that the frequency-distribution graphs of the sets to be differentiated do not overlap." In the early and late Cary samples there is some overlap in the frequency-distribution graphs and a split is only apparent in the triangular diagram. Yet the evidence seems sufficient to indicate that the correlation is valid on the basis of the triangular diagram alone. Had the variation which is present in the late Cary samples been present in the early Cary or Tazewell samples as well, the method would be of little value.

On the basis of the Tazewell and early Cary tills one might postulate that in any one till sheet there is a fair degree of homogeneity, but the wide range of mechanical compositions within the late Cary sheet make this seem somewhat disputable. It will be shown, however, that this variation is quite explainable and not contrary to the concept of homogeneity in individual till sheets.

If a sample falls within the area on the triangular diagram corresponding to the tentative age as determined in the field, it is felt that the dating of this sample is correct. On the other hand, samples which fall into the "wrong" group on the basis of field dating, unless they can be explained by known local variations in the field, are to be suspected and further field work is indicated. One rather noteworthy example of the value of this supposition was encountered with several samples collected in 1950 and tentatively assigned a late Cary age. The drift from which they were taken was rather close to the surface and on the basis of this evidence it was supposed that they represented the highest and hence the youngest till. Analysis showed, however, that texturally the samples belong to the early Cary drift and furthermore were located areally near and were very similar in mechanical composition to the early Cary samples of pairs 36 and 69. On the strength of this evidence the sections were reexamined in 1951 and it was dis-

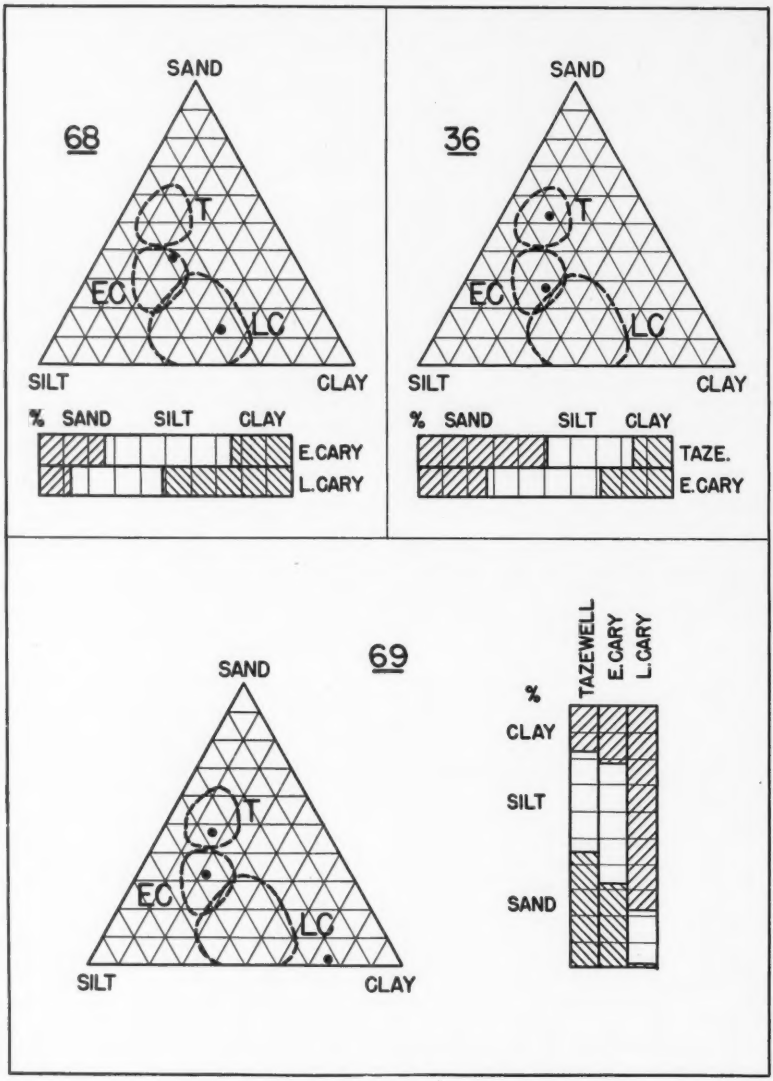


FIG. 4.—Comparison diagrams of multiple till samples collected from the same exposure (nos. 68, 36, and 69).

covered that, in fact, the till is of early Cary age with a very thin late Cary till above, in many places represented only by the soil profile (White, 1952).

### TEXTURAL COMPOSITION OF THE TILLS

Because of the number of samples and the analysis of three tills within the same area it is possible not only to discuss the textural composition of a particular till sheet, but also to compare one sheet with another. It is not within the scope of this report to discuss in detail the relative importance of various factors in drift composition. Indeed, such discussion must await the collection of further data on carbonate content, heavy minerals, clay character, lithologic variations and other physical characteristics (For lithologic variations in part of the area see White, 1953).

In figure 5 the averages for the percentage of sand and of clay have been plotted on bar graphs. In figure 6 the ranges of the values plotted in figure 5 are also shown on bar graphs. Figure 5 indicates the average mechanical composition of the three tills and figure 6 shows at a glance the variation in the mechanical compositions of the individual tills.

Tazewell till over the entire area is essentially a sandy till since its mean size ranges from .042 mm to .125 mm and averages .072 mm. Early Cary till, in contrast to the Tazewell till, is silty with an average mean size of .018 mm and a range from .0125 mm to .039 mm. As shown in the triangular diagram the range in the textural composition of the two tills is not excessively large, particularly considering the size of the area from which the samples were taken. As shown in figure 6, the range in the percentages of sand and clay in these two tills is likewise moderately small. Based on 14 samples the variation in the Tazewell till of the percentage sand is 18 per cent and the clay is 13 per cent. For the early Cary till, based on 30 samples, the variation in the percentage sand is 20.5 per cent and clay is 14 per cent. From the bar graphs and the triangular diagram it is apparent that the percentage sand in the two tills is the factor which differentiates them.

Late Cary drift, in contrast to both the Tazewell and early Cary drifts, shows considerable variation in textural composition. This is apparent in both the triangular diagram (fig. 2) and the bar graphs (fig. 6). The till ranges from a silt till to a clay till with an average mean

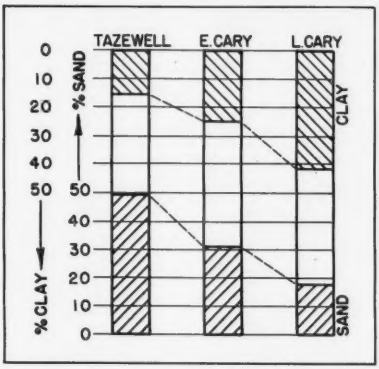


FIG. 5.—Average percentages of sand and clay in the Tazewell, early Cary, and late Cary tills.

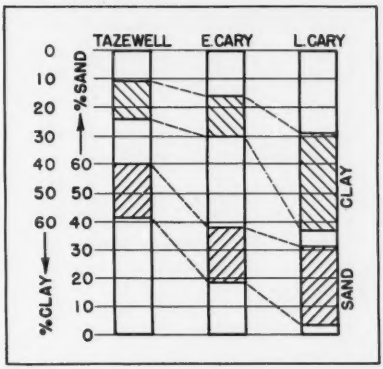


FIG. 6.—Range in percentages of sand and clay in the Tazewell, early Cary, and late Cary tills.

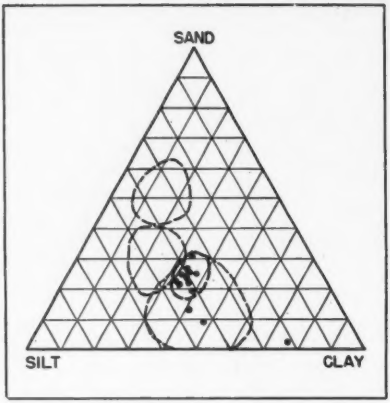


FIG. 7. Composition of late Cary till samples from the Medina lobe.

size of .0066 mm and a range in the mean size from .0014 mm to .013 mm. This variation shows as well in the bar graphs, for the percentage sand ranges from 4 per cent to 31 per cent, a range of 27 per cent, and the clay ranges from 29 per cent to 63 per cent, a range of 34 per cent, based on 32 samples. It thus appears that over the entire area under consideration the Tazewell and early Cary tills are essentially homogeneous while the late Cary till is quite heterogeneous.

All three tills show approximately the same degree of sorting, with sorting factors falling between the approximate limits of 3.00 to 7.50, but all do not show the same range of sorting factors. The Tazewell till is more limited in sorting, ranging from 4.04 to 5.87, a total range of 1.83. The early Cary till shows a wider range of sorting factors from 4.15 to 7.51, a total range of 3.36, and the late Cary shows a still wider range with sorting factors from 3.01 to 7.40 or a total range of 4.39.

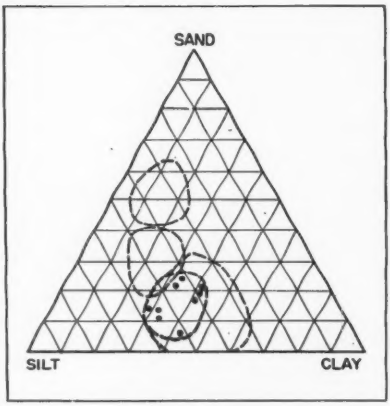


FIG. 8.—Composition of late Cary till samples from the Cuyahoga lobe.

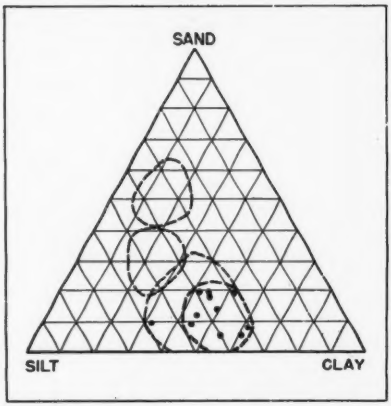


FIG. 9.—Composition of late Cary till samples from the Grand River lobe.

The late Cary ice advanced in three lobes, the Grand River lobe, the Cuyahoga lobe, and the Medina lobe, as shown in figure 1 (White, personal communication). These are, of course, projections from the major Lake Erie lobe. The Grand River lobe is the most marked, the other two are merely short projections, no more than "sublobes," but are here named for convenience of discussion. If each lobe is considered separately, the heterogeneity of the late Cary drift largely disappears. In figures 7, 8, and 9 the samples from the individual lobes have been plotted on separate triangular

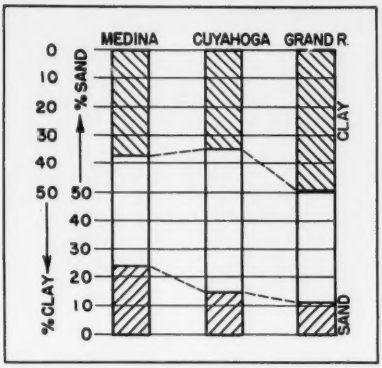


FIG. 10.—Average percentages of sand and clay in late Cary tills of the Medina, Cuyahoga, and Grand River lobes.

diagrams and the groups encircled. The boundary lines of figure 2 have been included for reference. Bar graphs similar to those in figures 5 and 6 have been plotted for the individual lobes in figures 10 and 11. In figure 7 three samples have been included which fall outside of the encircled area. Field evidence of nearby lacustrine silts and clays (White, personal communication) suggests that these samples are "contaminated" and their position outside of the concentration of samples on the triangular diagram also strongly supports this evidence. Sample 69c, which falls outside of the encircled groups on the triangular diagram, has been included in figures 2 and 7 since it is one of three samples collected at the same locality and is of undoubted late Cary age. The sample contains some rare pebbles and is believed to be a greatly contaminated till rather than a lacustrine clay contaminated by till.

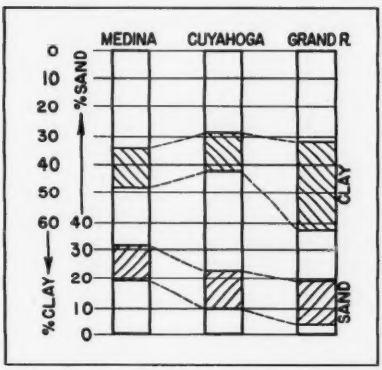


FIG. 11.—Range in percentages of sand and clay in late Cary tills of the Medina, Cuyahoga, and Grand River lobes.

Till in the Medina lobe is a silt till with an average mean size of .0091 mm and a range in the mean size from .013 mm to .0043 mm. Variations in the percentages of sand and clay are moderate indeed, the sand having a range of 10 per cent (not considering the samples known to be locally contaminated) and the clay a range of 15 per cent as shown in figure 11. The average mean size of the till in the Cuyahoga lobe is .0079 mm and in the Grand River lobe is .0037 mm. The large percentage of points concentrated in the Medina lobe suggests strongly that this is the "type" till of the late Cary advance and that the tills of the other two lobes have been contaminated, the till of the Cuyahoga lobe by silt and some clay and the till of the Grand River lobe predominantly by clay. This is further suggested by the bar graphs of the individual lobes (figs. 10 and 11) which show an increase in the percentage silt in the Cuyahoga lobe as compared to the Medina lobe and an increase in the percentage clay in the Grand River lobe as compared to both the Medina and the Cuyahoga lobes. The graphs also show a decrease in the percentage sand in the Cuyahoga and Grand River lobes as compared to the "type" till of the Medina lobe while the variation in the percentage sand in the three lobes remains about the same, suggesting that incorporation of sand has been minor as compared to incorporation of clay and silt. It also seems more likely that contamination of the load carried by an encroaching glacier would be by fine grained material, since a possible source of coarse material over a large area is somewhat obscure. A rather

uniform source of material is required, since a great variation in mechanical composition would result if irregularly distributed deposits of sorted coarse or fine materials were incorporated.

### TEXTURAL RELATIONS BETWEEN THE TILLS

In this paper and throughout the literature where other analyses are reported (Krumbein, 1933; Kay and Graham, 1943; Riecken *et al.* 1947, p. 437) it is interesting to note that in many cases where multiple Wisconsin tills are present the mean size or textural composition of the tills decreases upward from till to till. In the area of northeastern Ohio the local control of till texture has not been as dominant as has been asserted in other areas (Kruger, 1937; Flint, 1947, p. 105; 114–116; Crosby, 1896; Trefethen and Harris, 1933; Eskola, 1933). Krumbein recognized approximately the same situation in Illinois (1933, p. 397) and further expressed the view that unconsolidated surficial materials seem to have a greater effect on the textural composition than indurated bedrock, even when the latter is a relatively soft shale. Under these conditions what controlling factors would cause a successive decrease in mechanical composition upward?

Due to a protective coating of the bedrock by earlier tills, progressively less local bedrock material is made available for incorporation into the tills of the later ice advances. Hence a source of coarse material for the later tills would be limited largely to the till which mantles the surface; interstadial deposits such as dunes and local stream deposits; and the scattered bedrock exposures which escaped the mantling of the earlier tills or from which this mantle was removed by later erosion. In contrast, an increasing source of fine materials is introduced during the interstadial period in the form of lake clays and silts, and loess. It would be expected that, under these conditions, the lower till would reflect most the influence of the underlying bedrock while successively higher tills would reflect it to a lesser degree.

These factors seem to hold when the Wisconsin glaciation is considered. Whether they would hold for the pre-Wisconsin advances where interglacial periods are longer is a matter for speculation, but it would seem that during a long period of weathering and erosion influences favoring greater local variation in later drifts might obtain.

In summary, then, a decrease in grain size in successive Wisconsin tills could be due to a decreasing source of coarse material and an increasing source of fine material.

### FACTORS INFLUENCING THE TEXTURAL COMPOSITION OF TILL

The cause of the homogeneous character of the Wisconsin till sheets in northeastern Ohio provokes many questions, most of which the author feels neither qualified nor called upon to answer. However, a discussion of these points is of some value, if only to point out the need for further study on the origin of till materials.

Many workers (Kruger, 1937; Holmes, 1952; Flint, 1947, p. 105, 114-116; Crosby, 1896; Trefethen and Harris, 1933; Eskola, 1933) have expressed the belief that the mineralogic and lithologic composition of tills is of local derivation. Hence, it might be said, since the textural composition of a till is affected by the incorporation of local materials, that the textural composition would vary considerably depending upon the variation in local materials immediately upstream. If this were truly the case one could not expect to find homogeneity in the textural composition in an individual till sheet over such an area as is considered in this report.

Is it correct to say that till materials are locally derived? If one were to study the coarse fraction (especially pebbles and cobbles) of any till, he would come to the conclusion that that till had been locally derived. It appears that most workers who postulate local origin of till materials do so on the basis of such

evidence. To the knowledge of this author there are very few, if any, thorough studies of the clay fractions of tills in the literature. Would it not be expected that materials derived at some distances upstream be reduced to fine size and hence make up the clay portion of any till while locally derived materials make up the coarse portion?

It is apparent that, in part, the materials composing tills are of local origin, but it is this author's belief that they represent a smaller percentage of the material than is commonly supposed. Local materials, for the most part, possibly represent no more than 20 or 30 per cent of material which has been incorporated into till material already present in and beneath the advancing ice and originally accumulated at possibly great distances upstream. It is not denied that some portions of any till sheet may be largely locally derived (for example, sample #69c), but as a whole it is believed that the majority of material in an individual till sheet is derived at some distance upstream.

Another line of evidence which suggests that a large part of the material in a till sheet is not locally derived is the cumulative thickness of drift. In Illinois the thickness of drift in the Wisconsin drift areas is approximately 25 feet greater than the drift in the area outside of the Wisconsin drift borders (Leverett, 1899, p. 546, pl. XXIV). This 25 feet of drift could not have as its source the material beneath, since the removal of any of the lower and the subsequent replacement of that drift would not increase the total thickness.

If the large part of the material in a till is collected at distances considerably upstream, adequate time and distance is available to allow a thorough mixing of the material and the establishment of a rather uniform mechanical composition. Hence, when an advancing glacier moves into an area it can bring with it a "type" till with a certain limited range in mechanical composition. The incorporation of local materials is not sufficiently large to destroy the over-all uniformity of mechanical composition, but rather only to impress local variation such as is present in the late Cary tills of northeastern Ohio. As has been expressed previously the probable effect of local contamination would be to lower generally the average size of the material.

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FIGS. 1–9, MARCH, 1953

# A METHOD FOR THE SIZE ANALYSIS OF SAND ON A NUMBER FREQUENCY BASIS

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ABSTRACT

A method is proposed by which number frequency instead of weight may be used in the size analysis of sand. Random samples, taken from eight sieved sand samples representing two different stages of abrasion and periods of time, are counted and weighed to establish mean particle weights. A plot of these mean weights indicates that they are a function of sieve opening. This function is used in size analyses of the eight samples.

## INTRODUCTION

Standard practice in the size analysis of sand consists of regarding the weight of sand present on a sieve as an expression of number frequency. This technique has the obvious drawback of considering one large particle to be the equivalent of several small particles and has, on more than one occasion, caused difficulties in interpretation.

A method is proposed by which frequency instead of weight may be used in the size analysis of sand. Random samples are taken from eight seived sand samples representing two unlike stages of abrasion and two different periods of time. These random samples are counted and weighed to establish mean particle weights. A plot of these mean particle weights against their respective sieve range mid-points on double logarithm paper indicates that the weight of a sand particle is a power function of its intermediate diameter as expressed by the sieve opening. This means that mean particle weight may be directly determined from sieve range mid-point. The total weight of sand on a given sieve divided by the mean particle weight yields the number of sand particles present. The error involved in the random sampling is shown to be negligible.

Size analyses are performed on the eight sand samples using both arithmetic moments and readings from cumulative curves.

It is found desirable to use a succession of short sieve ranges in the modal area since, the smaller the range, the less error involved in assuming the sieve range mid-point to be the mean size.

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## TECHNIQUE

### Basic Equation

If the mean weight of one sand particle from a given sieve is known, this value may be divided into the total weight of sand on the sieve to find the number of particles present. Thus,

$$wt = w \cdot x \tag{1}$$

$$w = \frac{wt}{x} \tag{2}$$

$$x = \frac{wt}{w}. \tag{3}$$

Where $wt$ is total weight of sand, $x$ is the number of particles present, and $w$ is the mean weight of one particle.

The problem lies in determining $w$, the mean weight of one particle; for, if this can be accomplished, equation (3) $x = wt/w$ gives a direct reading of the

number of particles present. The writer found that by weighing a counted random sample of over 200 particles a value for $w$ could be obtained that would be representative, within small error limits, of the entire sand population on a given sieve. The random sample is counted, weighed, and $w$ is derived from (2) $w = wt/x$.

## Laboratory and Field Procedure

Eight sand samples were collected for this research, four from the beach at Sterling State Park, Michigan located on the western shore of Lake Erie and four from the Sylvania sandstone outcrops at Rockwood quarry near Rockwood, Michigan. The sand of the beach at Sterling State Park is of glacial-lake origin and is essentially subangular. The Sylvania sandstone is the basal Devonian formation in Michigan and is Lower Middle Devonian in age. It is quarried as a glass sand and is considered to be the product of aeolian deposition, having a rounded and frosted character.

The beach sand samples are lettered A, B, C, and D. Samples A, B, and C were collected down the beach, just waterward of the strand line. Sample B was taken 2000 feet south of A, Sample C was taken 2500 feet south of B, and Sample D was taken at half the distance (17 feet) between C and the crest of the beach. The current of Lake Erie runs from north to south in this area or from Sample A to Samples C and D.

The sandstone samples are numbered I, II, III, and IV. These samples were collected from a 25-foot quarry wall, Sample I immediately beneath the soil overburden, Sample II 10 feet from the top, Sample III 17 feet from the top, and Sample IV at the base of the exposure. The cementing material of the Sylvania sandstone in this area is calcium carbonate. Hydrochloric acid was used in the disaggregation of particles.

The eight samples were Ro-Tapped fifteen minutes each using the following succession of screens in millimeters: 7.93, 4.00, 2.00, 1.00, .50, .35, .250, .125, .088, and .062. The writer found that only the material lying on the screens 1.00, .50,

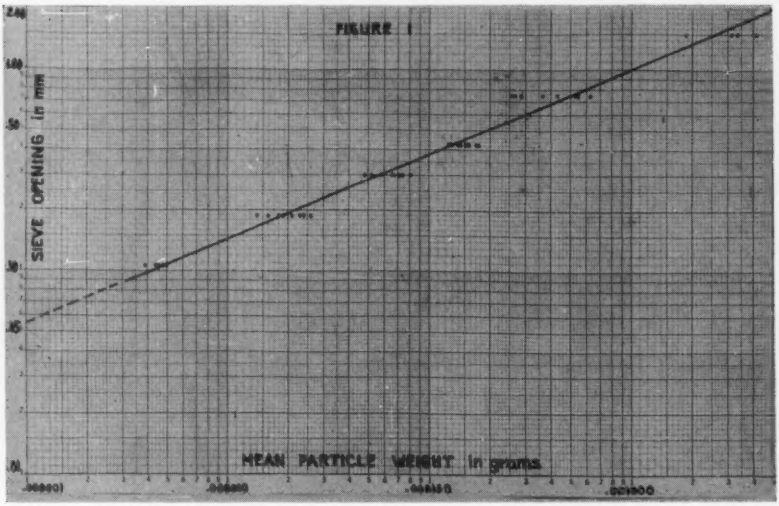


FIG. 1

.35, .250, .125, and .088 was suitable for analysis. The reason for this, which will be discussed more fully later, was that the material lying on the other screens did not follow the relation shown by figure 1.

The counting of the random samples taken from each sieve size was found to be best accomplished by scattering the grains over a concentrated area of $\frac{1}{4}'' \times \frac{1}{4}''$ graph paper. The horizontal columns on the graph paper were numbered and, by using a 7-power hand lens, the grains lying within each column could be counted quite rapidly.

The grains were then carefully transferred from the graph paper to a glass weighing bottle.

A Seeder-Kohlbusch, Inc. analytical balance, correct to $\pm .00005$ gram or to nearest ten thousandth of a gram was used for all weighings.

## ERROR FACTORS

### Density and Size

Two necessary requirements for finding a reliable mean weight from a counted random sample are that the items being sampled have (1) a similar density and (2) a restricted size range. A large majority of the sand and sandstone deposits have a similar density in that the principal constituent is quartz, which has a density of 2.65+. Contamination by the feldspars is not serious since the feldspars have densities quite similar to that of quartz. The heavy mineral content of sandstones is generally well below 1% and below 2 or 3% for beach sands.

The sand of the Sylvania sandstone is a glass sand and is pure quartz excepting a heavy mineral content of much less than 1%. The Lake Erie beach sand has a heavy mineral content of between 1% and 2% and a feldspar content, by estimation from cleavages and color, of between 10% and 20%.

The function of the sieves is to restrict the size range. The more narrowly the size range is restricted, the more reliable are the mean weights.

The sorting power exercised by the sieves, considering each particle to have a maximum, intermediate, and minimum diameter, is based on intermediate diameter. In the case of quartz, maximum diameter does not appear to increase appreciably without a relative increase in the important intermediate diameter (from inspection of figure 1).

### Random Sampling

The error of a random sample of known quantity taken from an infinite population follows the relation,

$$S_{\bar{X}} = S_X / \sqrt{n}$$

where $S_{\bar{X}}$ is the standard deviation of the random sample or the random error, $S_X$ is the standard deviation of an infinite population, and $n$ is the number of items in the random sample.

To obtain the upper limit of error for the random sampling procedure, $S_X$ must be assigned its maximum possible value. $S_X$ is maximized when the population has bunched at both extremes of the limiting range. By the laws of statistics, this $S_X$ may be evaluated at one half the limiting range.

Thus, in the case of sand samples, if the sieve range 1.00- .50 mm has limits to the mean weight of one particle the values .000999 gram and .000193 gram (from figure 1), and all the particles have either of these values but never an intermediate weight, then the $S_X$ of this distribution is

$$S_X = \frac{.000999 - .000193}{2} = \pm .000403 \text{ gram.}$$

If 200 particles are weighed to establish a mean weight, the error of that mean weight is

$$S_{\bar{X}} = \frac{.000403}{\sqrt{200}} = \pm .000028 \text{ gram.}$$

Possibly a more reasonable assumption is that the particle weights are uniformly distributed over the range. A uniform distribution has the largest standard deviation except for those where the population has gathered about both end-

members. From the laws of mathematical expectation, the standard deviation of a uniform distribution is equal to $\sqrt{1/12}$ times the limiting range.

Applying this to the same data as above,

$$S_x = \sqrt{1/12}\ (.000999 - .000193)$$
$$= \pm .000233 \text{ gram}$$
$$S_{\bar{x}} = \frac{.000233}{\sqrt{200}} = \pm .000017 \text{ gram.}$$

The above examples are based on a random sample of 200 particles from the sieve range 1.00–.50 mm. It is understood, however, that increasing the random sample or decreasing the sieve range results in a decrease in the error. For example, if 400 particles are counted in the sieve range .35–.25 mm where the mean weight limits (from Figure 1) are .000083 gram and .000037 gram, the error limit is

$$S_{\bar{x}} = \frac{(.000083 - .000037)}{2\sqrt{400}} = \pm .0000012 \text{ gram}$$

in the case where the population has bunched at the end-members and

$$S_{\bar{x}} = \frac{(.000083 - .000037)\sqrt{1/12}}{\sqrt{400}}$$
$$= \pm .0000006 \text{ gram}$$

in the case where the population is uniformly distributed.

All of these examples are comparatively small upper limits of error and should have very little effect on the mean weight manipulations.

### Approximate Numbers

Another factor which is conducive to error is the improper handling of approximate numbers. The mean particle weights are approximate numbers and are subject to certain mathematical limitations, viz., results are no more accurate than the least precise factor involved. For example, if 2.0000 grams of sand have a mean particle weight of .0010 gram, there are not 2000 particles present but 20xx particles present. The last two zeros are "pseudo" zeros. The writer has adopted the policy of using x's in place of all "pseudo" zeros so that there will be no confusion as to the number of significant digits.

### EXPERIMENTAL RESULTS

In the table below are listed the mean particle weights obtained from the random sampling of eight sand samples. The corresponding frequencies given are derived from equation (3) $x = wt/w$. There was no material larger than 1 mm in the Sylvania sandstone.

The scatter diagram shown on figure 1 represents a plot of the 44 mean particle weights listed in table 1 against their respective sieve range mid-points. The $X$ axis values correspond to the mean particle weights, and the $Y$ axis values correspond to the sieve openings. The plot is made on double logarithm paper. Power functions plot as straight lines on double logarithm paper.

There are two straight lines (called *regression lines*) which may be fitted through the dots of a scatter diagram unless all the dots fall on the same straight line. One of these lines is constructed to show unknown values of $X$ when $Y$ is known, the other to show unknown values of $Y$ when $X$ is known. The degree of reliance that can be placed on this calculation of the unknown variable is given by the correlation coefficient which is a standard statistical device used to show the linear relation between variables. The correlation coefficient takes values between $+1$ and $-1$. A value of $+1$ indicates a positive linear relationship between variables, a value of $-1$ indicates a negative linear relationship between variables, and a value of 0 indicates no linear relationship between variables.

The value of the correlation coefficient for the experimental mean particle weights and their corresponding sieve range mid-points is $+0.99132$.[1] A Monro-Matic desk calculator was used for the

[1] The procedure involved in computing the correlation coefficient may be found in most statistical texts.

TABLE 1.—*Weight and number in each grade of eight sand samples*

| Sieve range | Total Wt. of sand (gms) | Wt. of random sample (gms) | No. of grains in random sample | Mean Wt. of one grain (gms) | Sand frequency |
|---|---|---|---|---|---|
| | | Lake Erie beach sand | | | |
| | | Sample A | | | |
| 2.00 –1.00 | 0.2473 | 0.2473 | 130 | .001879 | 130 |
| 1.00 – .50 | 17.5437 | 0.1227 | 226 | .000543 | 32,32x |
| .50 – .35 | 15.5101 | 0.0431 | 286 | .000151 | 103,xxx |
| .35 – .250 | 39.7924 | 0.0156 | 238 | .000066 | 607,xxx |
| .250– .125 | 24.4219 | 0.0130 | 505 | .000026 | 949,xxx |
| .125– .088 | 0.1307 | 0.0012 | 250 | .0000048 | 27,xxx |
| | | Sample B | | | |
| 2.00 –1.00 | 2.9864 | 1.0489 | 250 | .004196 | 712 |
| 1.00 – .50 | 4.1213 | 0.1274 | 241 | .000529 | 7,796 |
| .50 – .35 | 16.4121 | 0.0611 | 439 | .000140 | 118,xxx |
| .35 – .250 | 51.3550 | 0.0198 | 341 | .000058 | 885,xxx |
| .250– .125 | 22.8633 | 0.0057 | 247 | .000023 | 99x,xxx |
| .125– .088 | 0.0500 | 0.0021 | 471 | .0000045 | 11,xxx |
| | | Sample C | | | |
| 2.00 –1.00 | 0.6965 | 0.6965 | 209 | .003332 | 209 |
| 1.00 – .50 | 6.7121 | 0.1257 | 200 | .000628 | 10,68x |
| .50 – .35 | 14.0777 | 0.0311 | 200 | .000156 | 90,6xx |
| .35 – .250 | 45.5970 | 0.0104 | 200 | .000052 | 877,xxx |
| .250– .125 | 29.2579 | 0.0048 | 200 | .000024 | 1,22x,xxx |
| .125– .088 | 0.1222 | 0.0010 | 200 | .0000050 | 24,xxx |
| | | Sample D | | | |
| 2.00 –1.00 | 0.9385 | 0.6282 | 200 | .003131 | 300 |
| 1.00 – .50 | 9.4286 | 0.0865 | 200 | .000432 | 21,8xx |
| .50 – .35 | 14.6810 | 0.0284 | 200 | .000142 | 103,xxx |
| .35 – .250 | 44.0960 | 0.0095 | 200 | .000048 | 93x,xxx |
| .250– .125 | 26.4280 | 0.0038 | 200 | .000019 | 1,39x,xxx |
| .125– .088 | 0.0700 | 0.0009 | 200 | .0000045 | 2x,xxx |
| | | Sylvania Sandstone | | | |
| | | Sample I | | | |
| 1.00 – .50 | 0.2073 | 0.0587 | 229 | .000257 | 807 |
| .50 – .35 | 5.4851 | 0.0418 | 327 | .000128 | 42,9xx |
| .35 – .250 | 20.3733 | 0.0270 | 367 | .000074 | 277,xxx |
| .250– .125 | 95.5801 | 0.0100 | 628 | .000016 | 6,00x,xxx |
| .125– .088 | 7.8009 | 0.0010 | 256 | .0000039 | 2,0xx,xxx |
| | | Sample II | | | |
| 1.00 –.50 | 2.1034 | 0.0572 | 200 | .000286 | 7,35x |
| .50 – .35 | 20.1908 | 0.0604 | 354 | .000171 | 118,xxx |
| .35 – .250 | 38.3009 | 0.0266 | 329 | .000081 | 474,xxx |
| .250– .125 | 48.2685 | 0.0153 | 847 | .000018 | 2,67x,xxx |
| .125– .088 | 2.2629 | 0.0026 | 596 | .0000044 | 51x,xxx |
| | | Sample III | | | |
| 1.00 – .50 | 4.7877 | 0.1247 | 340 | .000367 | 13,05x |
| .50 – .35 | 36.2284 | 0.0708 | 408 | .000174 | 208,xxx |
| .35 – .250 | 63.2300 | 0.0343 | 438 | .000071 | 807,xxx |
| .250– .125 | 37.4022 | 0.0043 | 301 | .000014 | 2,7xx,xxx |
| .125– .088 | 5.3686 | 0.0012 | 309 | .0000039 | 1,4xx,xxx |
| | | Sample IV | | | |
| 1.00 – .50 | 0.2662 | 0.0713 | 268 | .000266 | 1,00x |
| .50 – .35 | 14.1246 | 0.0441 | 351 | .000126 | 112,xxx |
| .35 – .250 | 25.7680 | 0.0346 | 517 | .000067 | 385,xxx |
| .250– .125 | 42.9475 | 0.0104 | 502 | .000021 | 2,08x,xxx |
| .125– .088 | 4.5830 | 0.0011 | 241 | .0000046 | 1,0xx,xxx |

computation. Since the correlation coefficient expresses *linear* relationship, the common logarithmic values of $X$ and $Y$ were used. This is due to the fact that plotting values on double logarithm paper is equivalent to plotting the logarithms of these values on ordinary graph paper.

For ease in manipulation of the logarithms, the mean weights values, $X$, were initially multiplied by $10^6$ and the sieve opening values, $Y$, multiplied by $10^1$. This has no bearing on the logarithmic relationship between variables since the base 10 cycles permit such changes in scale unit.

The proximity of $+0.99132$ to $+1$ means that, for all practical purposes, the logarithm of the weight of a sand particle is a positive linear function of the logarithm of its intermediate diameter. The two regression lines, expressed logarithmically, are

(4) $X=2.37535Y+0.62427$, and

(5) $Y=0.41371X-0.24925$.

Arithmetically they are

(4a) $Y=.054600X^{.42099}$, and

(5a) $Y=.056332X^{.41371}$.

This means that the $Y$ axis is cut at .0546 and .0563 and that the two slope angles are 22°50′ and 22°28′. Only (4a) has been constructed on Figure 1 since the lines are so similar.

Equations (4) and (5) are of much value because they may be used in the size analysis of sand. Thus, if the mean particle weight, $X$, of a population of sand has been determined, its value may may be multiplied by $10^6$ and the common logarithm of the result substituted into (5) $Y=0.41371X-0.24925$. This will yield the logarithmic value of $Y$, the mean sieve opening. Therefore, to find $Y$ in millimeters, its antilogarithm may be looked up and multiplied by 10. Of more importance because of its practical value in eliminating the time-consuming mean weight determination is the calculation of mean weight from sieve range mid-point by (4) $X=2.37535Y+0.62427$. Here the value of $Y$ is the common logarithm of the sieve opening times 10, and the mean particle weight is the antilogarithm of the value of $X$ times $10^6$.

## SIZE ANALYSIS OF SAMPLES

The material above 2 mm has been discarded in the analyses for two reasons: (1) it is not considered to be sand by any common classification of the sediments, and (2) it is essentially composed of igneous rock fragments, invertebrate shells, and picnic debris in the beach sand samples.

The material on the screen .088–. 062 mm is not used because it does not follow the relation shown by Figure 1, i.e., 491 particles[2] from Sample II weighed .0004 gram, and 344 particles from Sample III weighed .0003 gram. Clearly these mean particle weights are less than .000001 gram and fall entirely off the scatter diagram. It is regrettable that this fine material must be ignored since, in so doing, a great many particles by number frequency are eliminated from consideration. Since, however, some sand classifications have lower limits larger than .088 mm (viz. Alling: 1−.1 mm =sand; .1−.01=silt), it is theoretically possible to get a rather good "sand reading" using as limits 2−.088 mm.

The writer has used arithmetic moments in the size analyses of the samples. The mean is the average size of all the particles, and the standard deviation is the sorting factor or "spread" about the mean. A fairly good skewness reading can be had from Pearson's skewness, $SK=\frac{\text{mean-mode}}{\text{standard deviation}}$. Here positive values indicate an excess of material on the fine side of the mean, and vice versa.

Size analyses have been made by both equations (4) and (5).
Analyses by equation (5) follow:

[2] Counted under a 125-power microscope.

Lake Erie Beach Sand
Sample A

| $d$ | $f$ | $fd$ | $fd^2$ |
|---|---|---|---|
| 1.2741 | 130 | 160 | 208 |
| .7641 | 32,32x | 24,94x | 18,79x |
| .4490 | 130,xxx | 46,2xx | 20,8xx |
| .3115 | 607,xxx | 187,xxx | 59,1xx |
| .2168 | 949,xxx | 206,xxx | 44,1xx |
| .1078 | 27,xxx | 2,9xx | 32x |
| | 1,718,xxx | 467,xxx | 143,9xx |

$$a \text{ (mean)} = fd/f = \frac{467,xxx}{1,718,xxx} = .272$$

$$S_D \text{ (standard deviation)} = \sqrt{(fd^2/f) - \bar{d}^2}$$

$$= \sqrt{.0830 - .0739} = .0995$$

$$SK \text{ (skewness)} = \frac{\bar{d} - \text{mode}}{S_D} = \frac{.272 - .217}{.0995} = +.55$$

| Sample B | Sample C | Sample D |
|---|---|---|
| $d$ | $d$ | $d$ |
| 1.776 | 1.615 | 1.574 |
| .7542 | .8096 | .6935 |
| .4351 | .4550 | .4377 |
| .3022 | .2888 | .2859 |
| .2061 | .2098 | .1905 |
| .1049 | .1096 | .1049 |
| $\bar{d} = .262$ | $\bar{d} = .253$ | $\bar{d} = .241$ |
| $S_D = .0806$ | $S_D = .0707$ | $S_D = .0781$ |
| $SK = +.70$ | $SK = +.61$ | $SK = +.64$ |

Sylvania Sandstone

| Sample I | Sample II | Sample III | Sample IV |
|---|---|---|---|
| $d$ | $d$ | $d$ | $d$ |
| .5594 | .5847 | .6483 | .5674 |
| .4193 | .4726 | .4761 | .4166 |
| .3342 | .3470 | .3286 | .3208 |
| .1774 | .1862 | .1678 | .1985 |
| .0989 | .1040 | .0989 | .1059 |
| $\bar{d} = .165$ | $d = .205$ | $\bar{d} = .191$ | $\bar{d} = .192$ |
| $S_D = .0510$ | $S_D = .0818$ | $S_D = .1082$ | $S_D = .0742$ |
| $SK = -.24$ | $SK = +.24$ | $SK = +.21$ | $SK = -.09$ |

When equation (4) is used, the mean particle weight for any given sieve is fixed (as corresponding to the sieve midpoint). The same sieve succession for all eight samples was used.

| $d$ | $w$ |
|---|---|
| 1.500 | .0026174 |
| .750 | .00050331 |
| .425 | .00013089 |
| .300 | .000057227 |
| .1875 | .000018739 |
| .1065 | .0000048891 |

Results of analyses by equation (4) follow:

Lake Erie Beach Sand

| Sample A | Sample B | Sample C | Sample D |
|---|---|---|---|
| $\bar{d} = .244$ | $\bar{d} = .248$ | $\bar{d} = .236$ | $\bar{d} = .240$ |
| $S_D = .0952$ | $S_D = .0808$ | $S_D = .0764$ | $S_D = .0835$ |
| $SK = +.60$ | $SK = +.74$ | $SK = +.63$ | $SK = +.63$ |

Sylvania Sandstone

| Sample I | Sample II | Sample III | Sample IV |
|---|---|---|---|
| $\bar{d} = .176$ | $\bar{d} = .207$ | $\bar{d} = .211$ | $\bar{d} = .188$ |
| $S_D = .0484$ | $S_D = .0718$ | $S_D = .0901$ | $S_D = .0475$ |
| $SK = -.23$ | $SK = +.28$ | $SK = +.26$ | $SK = +.04$ |

Evidently the equation (4) readings are not as accurate as the (5) readings since the mean sieve openings are arbitrary. But the divergence between the sieve range mid-point and the true mean size will tend to decrease as the sieve range decreases. Therefore, when equation (4) is being used, it is desirable to use as many sieves as possible, especially in the modal range where small differences in the mean size and weight cause large number frequency differences.

In order to show how the frequency cumulative curves differ from the standard weight cumulative curves, these curves have been drawn on figures 2 through 9. The sand frequencies used are those derived from the experimental mean weights.

Table 2 lists the relative percentages for number frequency by both equation (4) and (5) and for straight weight. This is given for all eight samples. The discrepancies between the equation (4) and (5) frequencies can be noted.

Figures 2 through 9 demonstrate how the weight curves fall on the coarse side of the frequency curves by reason of regarding one large grain to be the equivalent of several small grains.

Table 3 contains a listing of the standard size analysis methods applied to each of the curves. The methods used are

$$Md \text{ (median)} = P_{50}$$

$$So \text{ (sorting)} = \sqrt{Q_{25}/Q_{75}}$$

$$SKg \text{ (skewness)} = \frac{Q_{25} - Q_{75}}{Md^2}$$

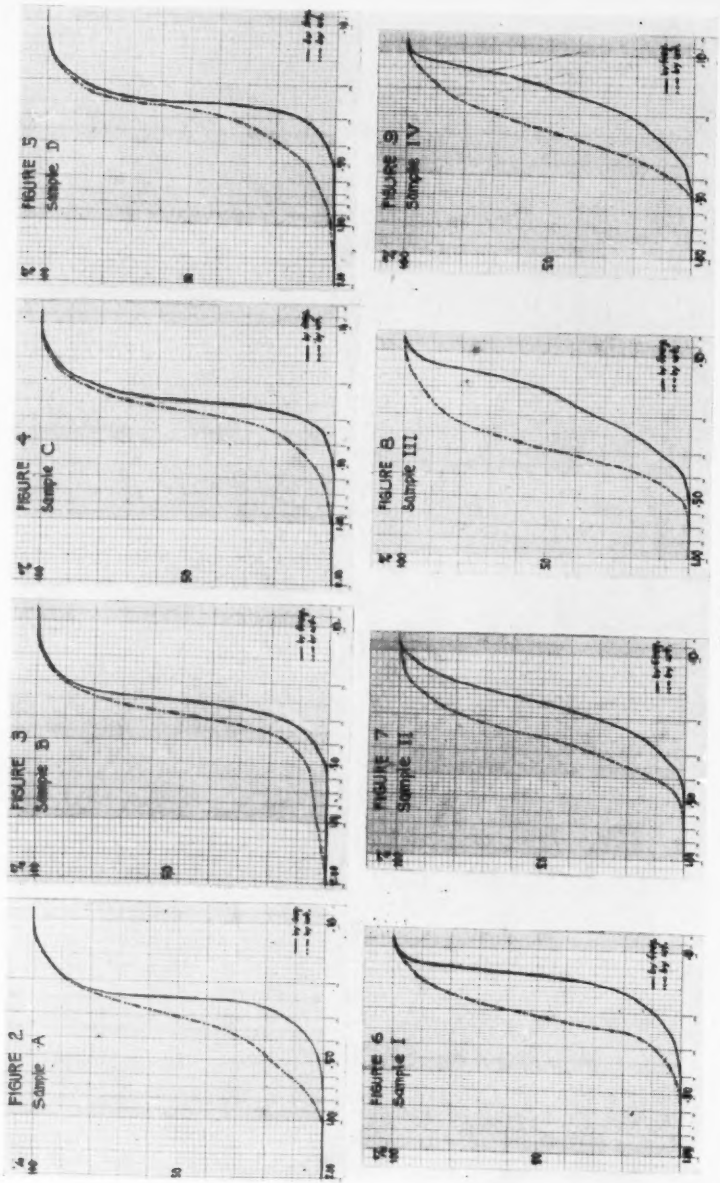
FIGURE 2
Sample A
FIGURE 3
Sample B
FIGURE 4
Sample C
FIGURE 5
Sample D
FIGURE 6
Sample I
FIGURE 7
Sample II
FIGURE 8
Sample III
FIGURE 9
Sample IV

FIGS. 2–9

TABLE 2.—*Relative percentages for number frequency by equations (4) and (5) and for straight weight*

| Sieve Range | Freq. by (4) | % | Freq. by (5) | % | Wt. | % |
|---|---|---|---|---|---|---|
| | | | Lake Erie Beach Sand | | | |
| | | | Sample A | | | |
| 2.00 –1.00 | 91 | 0.0 | 130 | 0.0 | 0.2473 | 0.3 |
| 1.00 – .50 | 34,857 | 1.6 | 32,32x | 1.9 | 17.5437 | 18.0 |
| .50 – .35 | 118,50x | 5.4 | 103,xxx | 6.0 | 15.5101 | 15.9 |
| .35 – .250 | 695,34x | 31.9 | 607,xxx | 35.3 | 39.7924 | 40.8 |
| .250– .125 | 1,303,3xx | 59.8 | 949,xxx | 55.2 | 24.4219 | 25.0 |
| .125– .088 | 26,8xx | 1.2 | 27,xxx | 1.6 | 0.1307 | 0.1 |
| | 2,178,9xx | 99.9 | 1,718,xxx | 100.0 | 97.6461 | 100.1 |
| | | | Sample B | | | |
| 2.00 –1.00 | 1,141 | 0.1 | 712 | 0.0 | 2.9864 | 3.1 |
| 1.00 – .50 | 8,189 | 0.4 | 7,796 | 0.4 | 4.1213 | 4.2 |
| .50 – .35 | 125,39x | 5.5 | 118,xxx | 5.9 | 16.4121 | 16.8 |
| .35 – .250 | 897,39x | 39.7 | 885,xxx | 43.8 | 51.3550 | 52.5 |
| .250– .125 | 1,220,1xx | 53.9 | 99x,xxx | 49.0 | 22.8633 | 23.4 |
| .125– .088 | 10,2xx | 0.5 | 11,xxx | 0.5 | 0.0500 | 0.5 |
| | 2,262,4xx | 100.1 | 2,02x,xxx | 99.6 | 97.7861 | 100.5 |
| | | | Sample C | | | |
| 2.00 –1.00 | 266 | 0.0 | 209 | 0.0 | 0.6965 | 0.7 |
| 1.00 – .50 | 13,336 | 0.5 | 10,68x | 0.5 | 6.7121 | 7.0 |
| .50 – .35 | 107,55x | 4.3 | 90,6xx | 4.1 | 14.0777 | 14.2 |
| .35 – .250 | 796,77x | 13.8 | 877,xxx | 39.5 | 45.5970 | 47.3 |
| .250– .125 | 1,561,4xx | 62.3 | 1,22x,xxx | 54.9 | 29.2579 | 30.4 |
| .125– .088 | 25,0xx | 1.0 | 24,xxx | 1.1 | 0.1222 | 0.1 |
| | 2,504,4xx | 99.9 | 2,22x,xxx | 100.1 | 96.4634 | 99.7 |
| | | | Sample D | | | |
| 2.00 –1.00 | 359 | 0.0 | 300 | 0.0 | 0.9385 | 0.9 |
| 1.00 – .50 | 18,733 | 0.8 | 21,8xx | 0.9 | 9.4286 | 9.4 |
| .50 – .35 | 112,16x | 4.8 | 103,xxx | 4.2 | 14.6810 | 15.3 |
| .35 – .250 | 770,55x | 33.1 | 93x,xxx | 37.8 | 44.0960 | 46.1 |
| .250– .125 | 1,410,3xx | 60.6 | 1,39x,xxx | 56.5 | 26.4280 | 27.6 |
| .125– .088 | 14,3xx | 0.6 | 2x,xxx | 0.8 | 0.0700 | 0.1 |
| | 2,326,5xx | 99.9 | 2,46x,xxx | 100.2 | 95.7421 | 99.4 |
| | | | Sylvania Sandstone | | | |
| | | | Sample I | | | |
| 1.00 – .50 | 412 | 0.0 | 807 | 0.0 | 0.2073 | 0.2 |
| .50 – .35 | 41,907 | 0.6 | 42,9xx | 0.5 | 5.4851 | 4.2 |
| .35 – .250 | 356,01x | 5.0 | 277,xxx | 3.3 | 20,3733 | 15.7 |
| .250– .125 | 5,100,6xx | 71.9 | 6,00x,xxx | 72.3 | 95.5801 | 73.8 |
| .125– .088 | 1,595,6xx | 22.5 | 2,0xx,xxx | 24.1 | 7.8009 | 6.0 |
| | 7,094,5xx | 100.0 | 8,3xx,xxx | 100.2 | 129.4467 | 100.0 |
| | | | Sample II | | | |
| 1.00 – .50 | 4,179 | 0.1 | 7,35x | 0.2 | 2.1034 | 1.9 |
| .50 – .35 | 154,26x | 4.0 | 118,xxx | 3.1 | 20.1908 | 18.2 |
| .35 – .250 | 669,28x | 17.3 | 474,xxx | 12.6 | 38.3009 | 34.5 |
| .250– .125 | 2,575,8xx | 66.6 | 2,67x,xxx | 70.8 | 48.2685 | 43.4 |
| .125– .088 | 462,9xx | 12.0 | 51x,xxx | 13.5 | 2.2629 | 2.0 |
| | 3,866,4xx | 100.0 | 3,77x,xxx | 100.2 | 111.1265 | 100.0 |

TABLE 2.—(*Continued*)

| Sieve Range | Freq. by (4) | % | Freq. by (5) | % | Wt. | % |
|---|---|---|---|---|---|---|
| | | | Sample III | | | |
| 1.00 – .50 | 9,512 | 0.2 | 13,05x | 0.3 | 4.7877 | 3.3 |
| .50 – .35 | 276,79x | 6.2 | 208,xxx | 4.1 | 36.2284 | 24.6 |
| .35 – .250 | 1,104,9xx | 24.6 | 807,xxx | 15.8 | 63.2300 | 43.0 |
| .250– .125 | 1,996,0xx | 44.5 | 2,7xx,xxx | 52.9 | 37.4022 | 25.4 |
| .125– .088 | 1,098,1xx | 24.5 | 1,4xx,xxx | 27.4 | 5.3686 | 3.6 |
| | 4,485,3xx | 100.0 | 5,1xx,xxx | 100.5 | 147.0169 | 99.9 |
| | | | Sample IV | | | |
| 1.00 – .50 | 529 | 0.0 | 1,00x | 0.0 | 0.2662 | 0.3 |
| .50 – .35 | 107,91x | 2.9 | 112,xxx | 3.1 | 14.1246 | 16.1 |
| .35 – .250 | 450,28x | 11.9 | 385,xxx | 10.7 | 25.7680 | 29.4 |
| .250– .125 | 2,291,9xx | 60.5 | 2,08x,xxx | 57.8 | 42.9475 | 49.0 |
| .125– .088 | 937,4xx | 24.7 | 1,0xx,xxx | 27.8 | 4.5830 | 5.2 |
| | 3,788,0xx | 100.0 | 3,6xx,xxx | 99.4 | 87.6893 | 100.0 |

TABLE 3.—*Standard size analysis methods applied to the curves of figures 2 through 9*

| By Weight | | By Number Frequency | |
|---|---|---|---|
| | Lake Erie Beach Sand | | |
| | Sample A | | |
| $P_{50}=.305$<br>$Q_{25}=.420$<br>$Q_{75}=.250$ | $Md = .305$<br>$So = 1.30$<br>$SKg=1.13$ | $P_{50}=.249$<br>$Q_{25}=.261$<br>$Q_{75}=.236$ | $Md = .249$<br>$So = 1.05$<br>$SKg=0.99$ |
| | Sample B | | |
| $P_{50}=.290$<br>$Q_{25}=.342$<br>$Q_{75}=.254$ | $Md = .290$<br>$So = 1.16$<br>$SKg=1.03$ | $P_{50}=.250$<br>$Q_{25}=.277$<br>$Q_{75}=.233$ | $Md = .250$<br>$So = 1.09$<br>$SKg=1.03$ |
| | Sample C | | |
| $P_{50}=.262$<br>$Q_{25}=.334$<br>$Q_{75}=.239$ | $Md = .272$<br>$So = 1.18$<br>$SKg=1.08$ | $P_{50}=.245$<br>$Q_{25}=.264$<br>$Q_{75}=.224$ | $Md = .245$<br>$So = 1.09$<br>$SKg=0.98$ |
| | Sample D | | |
| $P_{50}=.272$<br>$Q_{25}=.347$<br>$Q_{75}=.245$ | $Md = .272$<br>$So = 1.19$<br>$SKg=1.14$ | $P_{50}=.249$<br>$Q_{25}=.262$<br>$Q_{75}=.231$ | $Md = .249$<br>$So = 1.06$<br>$SKg=0.98$ |
| | Sylvania Sandstone | | |
| | Sample I | | |
| $P_{50}=.211$<br>$Q_{25}=.245$<br>$Q_{75}=.178$ | $Md = .211$<br>$So = 1.18$<br>$SKg=0.98$ | $P_{50} = .132$<br>$Q_{25}=.151$<br>$Q_{75}=.126$ | $Md = .132$<br>$So = 1.10$<br>$SKg=1.09$ |
| | Sample II | | |
| $P_{50}=.257$<br>$Q_{25}=.329$<br>$Q_{75}=.207$ | $Md = .257$<br>$So = 1.26$<br>$Sig = 1.03$ | $P_{50}=.172$<br>$Q_{25}=.216$<br>$Q_{75}=.144$ | $Md = .172$<br>$So = 1.23$<br>$SKg=1.05$ |
| | Sample III | | |
| $P_{50}=.291$<br>$Q_{25}=.355$<br>$Q_{75}=.241$ | $Md = .291$<br>$So = 1.21$<br>$SKg=1.01$ | $P_{50}=.153$<br>$Q_{25}=.266$<br>$Q_{75}=.123$ | $Md = .153$<br>$So = 1.36$<br>$SKg=1.18$ |
| | Sample IV | | |
| $P_{50}=.240$<br>$Q_{25}=.312$<br>$Q_{75}=.188$ | $Md = .240$<br>$So = 1.29$<br>$SKg=1.02$ | $P_{50}=.147$<br>$Q_{25}=.195$<br>$Q_{75}=.122$ | $Md = .147$<br>$So = 1.27$<br>$SKg=1.10$ |

EVALUATION

Equation (5) $Y=0.41371X-0.24925$ yields more accurate results than equation (4) $X=2.37535Y+0.62427$ because mean particle weight has been determined and is used to find mean size; whereas in equation (4) mean size has been taken arbitrarily to be the sieve range mid-point and is used to find mean particle weight. This may be seen from a plot of the beach sand mean sizes along the beach, using the results of both equations.

Equation (5) Size Means

direction of current

N ⟶ S

| Sample A | Sample B | Sample C | | away |
|---|---|---|---|---|
| .272 | .262 | .253 | | from |
| | | Sample D | | strand |
| | | .241 | ↓ | line |

Equation (4) Size Means

direction of current

N ⟶ S

| Sample A | Sample B | Sample C | | away |
|---|---|---|---|---|
| .244 | .248 | .236 | | from |
| | | Sample D | | strand |
| | | .240 | ↓ | line |

The equation (5) size means conform with the accepted theory that fine material outruns the coarse in the direction of travel. The equation (4) size means do not conform.

Equation (4), however, has a much greater practical significance than equation (5) because it eliminates random sampling to find the mean particle weights. The writer suggests that equation (4) can be made as valuable as equation (5) by using a succession of short sieve ranges through the modal area. This has the effect of reducing the error involved in assuming the sieve range mid-point to be the mean size by reducing the size range.

Evidently relatively small errors in mean weight (arising from divergence in mean size from sieve mid-point) cause quite large differences in sand frequency, especially when a considerable weight of sand is present. Therefore, short sieve ranges not only reduce the size ranges but also the weights of sand present.

The sand used in finding the mean weights for the relation shown in figure 1 is both rounded and subangular in character and represents Devonian and Recent time. This is a fairly good indication that the relation is a characteristic of of sand and not of locality.

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FIGS. 1, 2, MARCH, 1953

## NOTES

# TRANSPORT AND ROUNDING OF LARGE BOULDERS IN MOUNTAIN STREAMS

MAXWELL GAGE
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On the floors and terrace treads of mountain valleys it is not unusual to find a scattering of exceptionally large boulders, far beyond the competence of the existing stream under conditions of normal flow, or even of normal flood discharge. Those obviously derived from nearby ungraded valley walls by gravitation alone present no problem, but the question of mode of transportation arises where lithology demands the source to have been some distance upstream. Large boulders are known to remain stationary for many years or even decades, as shown by growth of vegetation upon them, or by the stability of man-made structures attached to them, and this even in situations exposed to the full force of floods. Boulders stranded upon terraces are likely to remain undisturbed for much longer periods. In all cases, the average rate of progress for large blocks is obviously very slow compared with that for the bulk of the floodplain alluvium.

The writer is aware of four explanations that have been suggested for the presence of immense boulders on valley-floors or fans remote from the nearest possible source. They are: ice-transport during earlier glaciation of the region; mudflow-transport; water-traction by rare floods of cataclysmic proportions (not sharply distinguished from the previous case); and irregular, intermittent progress downvalley due to periodic erosion of alluvium under the downstream side of a boulder providing a depression into which it may be rolled or pushed by pressure of flood waters. Any or all of these may have been involved in the transport of a particular boulder to its present position.

This note is intended as an addendum to Trowbridge's account of the last mechanism (1911, pp. 741–743). A qualitative analogy with the traction of small pebbles by tiny rainwash rivulets suggested to Trowbridge that once a boulder has been upset, its momentum may enable it to advance several times the length of its diameter if there is an appreciable gradient.

In the valley of a steep mountain stream draining from Griffiths Glacier, one of the smaller glaciers in the New Zealand Alps, the writer recently observed a variation of this mechanism which seems to afford large boulders greater momentum at the initial upset, and thus improves the chances that they will roll an appreciable distance before coming to rest. The stream in question was vigorously entrenching the alluvium of an earlier aggradational phase. Numerous blocks weighing probably from ten to fifty tons, and judged to be well beyond the competence of the stream except during abnormal flooding, were found resting in the bed of the stream. They had been disturbed recently, as parts of their surfaces retained the brownish-yellow superficial stain acquired while buried in alluvium. Similar blocks, in various stages of re-excavation, were exposed in steep, unstable alluvial banks. It was not possible to tell how far a particular boulder had travelled, but

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it seems reasonable that because of the greater momentum acquired in falling or sliding distances of up to ten feet at the moment of release, the undermining of the banks would have set in motion larger boulders than could be affected by Trowbridge's process, and increased the probability that any boulder, once moved, would have travelled an appreciable distance before coming to rest. Furthermore, undermining is most active when a stream is above normal flow, and it then also has greater power to maintain the motion of dislodged blocks, and to deflect them towards the downstream direction.

The importance of this mechanism in sedimentation depends largely upon how often it would have the opportunity to function. The opportunity afforded through alternations of lateral and vertical corrosion by streams in response to base-level changes would in general be infrequent in relation to the endurance of a boulder under chemical weathering while at rest. On the other hand, alternations of aggradation and re-excavation from other causes would occur frequently in mountainous regions. Prominent terraces carved from earlier fill have been correlated with more important climate fluctuations lasting through hundreds or thousands of years. Minor, more rapid oscillations have been ascribed to lesser climate changes, and to deforestation, re-afforestation, hydraulic mining, erection of dams, irrigation and river-control works. On a still smaller scale, pulses or "waves" of aggradation are often recognizable in transit down mountain torrents. The origin of such pulses can sometimes be traced to the occurrence of a particular landslip, or to the mobilization of scree-slopes by an earthquake. Opportunities for large blocks to be moved are therefore likely to be rather frequent in the mountain-stream environment, unless complete excavation of fill happens to deposit a boulder upon the stripped rock floor. Further transport then must await the rare flood of exceptional discharge, or size-reduction and undermining by direct abrasion of both boulder and rock floor.

Large blocks may be found that have only recently arrived upon the active river-bed after some kind of gravitational transport down a steep valley-side. If lithologically capable of acquiring roundness, they may already show the beginnings of rounding of the lower portions that are within reach of the abrasive tools of the stream. Successive revolutions in the course of rolling-transport are necessary to provide an opportunity for rounding of the remainder of the surface. A high degree of rounding of large blocks of tough, resistant rock is more likely to be an indirect consequence of this process than a direct consequence of the rolling action, which by knocking off corners and edges, contributes to increased sphericity and reduction of size rather than to reduction of angularity.

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TROWBRIDGE, A. C. (1911) The terrestrial deposits of Owens Valley, California: Jour. Geology, vol. 19, pp. 706–747.

# PARA-RIPPLES IN LIMESTONE WITH SPECIAL REFERENCE TO OCCURRENCES IN THE MISSISSIPPIAN BOONE FORMATION

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The occurrence of large ripple marks in limestone warrants their notation and description because they are relatively uncommon and because of their indication of the conditions under which the sediments in which they are developed were deposited.

Large current ripple marks (para-ripples) occur near the top of the Boone limestone of Mississippain age where it is exposed in a stream bed at Morrow, Washington County, Arkansas (fig. 1).

Cornish (1901) in England, Kindle (1932) in Canada, and Bucher (1919) in the United States have been important contributors to the study of large current ripples as they are being formed today on the continental shelf, and as they occur in the sedimentary rocks of the geologic column. "The first attempt at a systematic discussion for an adequate interpretation of the sedimentary record" was that of Bucher in 1919.

"Large current ripple marks are common on tidal flats where they form more or less subparallel ridges that on open shores invariably trend at right angles to the shoreline, and in bays and estuaries in trending at right angles to the shorelines of these may run parallel with the general shoreline" (Cornish, 1901).

Large fossil current ripples in limestone and dolomite strata have been observed at various localities in this country. The following list is taken from Bucher (1919).

1. The Lower Ordovician dolomites in Illinois.
2. The Middle Ordovician Trenton at a number of places in New York and Ontario.
3. The Lower Silurian Brassfield limestone at a number of places in Kentucky and Ohio.
4. The younger Silurian limestones in Ohio and New York.
5. The Devonian limestones in Ohio and Ontario.
6. The Mississippian limestones in Iowa.

Study of the present-day and fossil current ripples of the above type forming, and formed, in calcareous sediments reveals the following characteristics and environmental conditions (as given by Bucher (1919) and Kindle (1932)):

1. The ripples range from asymmetrical to symmetrical.
2. The crests are broadly-rounded, and but rarely show distinct crest-lines.
3. The material of the ripples is fragmental with a heterogeneous arrangement.
4. Measurements made on some representative examples in limestones:
   (a) Wave-length (crest to crest) = 3 to 7 feet.
   (b) Amplitude (elev. of ripple ridge above trough) = 2 to 6 inches.
   (c) Vertical form index (ripple index, wave length/amplitude) = 10 to 18.
5. Granular sediments are essential to their formation.
6. Tidal currents are the only marine currents that flow parallel with the shoreline in which sufficient velocities are found over wide areas to form such ripples.
7. There is similarity of form between the large fossil ripples and some of the tidal para-ripples forming at the present time.
8. A sea having sufficient connection with the open ocean to allow relatively high tides.
9. A depth small enough to permit strong action on the bottom sediments by wind-drift and tidal current action combined.

FIG. 1.—Para-ripples in the Boone formation (Mississippian) at Morrow, Washington County, Missouri.

FIG. 2.—Symmetrical profile of para-ripples shown in figure 1.

10. Sufficient rate of sedimentation to insure preservation of the ripples.
11. Strong tidal currents are found only in water bodies which are in direct open connection with the sea and not in land-locked seas.

The facts about the para-ripples that occur in the Boone limestone at Morrow follow (figs. 1 and 2):

1. The area of exposure is about 20 by 200 feet.
2. The number of ripples that are well shown is 44.
3. The ripples are composed of a heterogeneous mixture of fragments of brachiopods, bryozoa, and crinoid columnals.
4. The ripples range from symmetrical to asymmetrical.
5. The ripple wave-length is approximately 4 feet.
6. The ripple amplitude is 3 to 4 inches.
7. The vertical form index is 13 to 15.
8. The ripples are notably regular in dimensions and in trend which is N. 70° E.
9. The asymmetry (if primary) of some of ripples would indicate that the currents were from the northwest.

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## REVIEW

*Geology of the Whittier-La Habra Area, Los Angeles County, California*, by Charles J. Kundert, State of California Department of Natural Resources, Division of Mines Special Report 8, March 1952. pp. 22; 3 pls.; figs. 19. 50 cents.

This report is primarily a good description of the areal geology of a local area along the south side of the Puente Hills. It appears to be a competent report on the stratigraphy, structure, and other aspects of the local geology, including areal map, structure sections, and other good illustrations.

Probably of more interest to the general reader are the discussions of the paleontology and lithology of the late Tertiary rocks covering most of the mapped area. Faunal lists of many macro- and micro-fossil collections are presented and briefly discussed. The petrology of the sandstones and conglomerates suggest a source in the San Gabriel Mountains to the north, and some of these strata with graded bedding include other features suggesting turbidity current deposition. The author states —Any explanation proposed to account for the deposition of conglomerates must fulfill three requirements: (1) it must suggest an agent capable of carrying and depositing boulders and cobbles of "hard" rocks together with "soft" rocks of comparable grade sizes; (2) it must allow final deposition at least to have taken place in deep waters; and (3) it must explain the graded bedding.

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